Specification for expanding geopolymer applications in ground engineering

Final Edition August 2022

Contents

Introduction and use of this specification

General

The Specification for the application and use of expansive geopolymers in Geotechnical Engineering (2022) is the first edition of what, it is hoped, will become the standard industry document for the specification of expanding geopolymer use for construction projects.

The expanding geopolymer process can be defined as the injection of multi-component material comprising a resin and a reagent/hardener to generate an expansive structural geopolymer grout.

Applications include:

- Improving the load-bearing capacity of soils under foundations and paving
- Remediation of structures that have suffered settlement
- Real-time displacement control
- Reduction of the hydraulic conductivity of soils and rocks
- Treatment of soils prone to shrinkage and swelling
- Void filling
- Leak Sealing
- Liquefaction protection
- Geopolymer columns

The injection process is carried out from a self-contained injection unit equipped with the mixing, pumping and component assembly, with a pipe and injection nozzle connection. The geopolymer grout mix process generates a chemical reaction known as polymerisation, enabling the material to expand volumetrically and change state from liquid to solid. The expansion process (usually within the first 60 seconds) is followed by the curing of the geopolymer. The solidified geopolymer typically nears its final mechanical properties in less than 15min. The specific technical properties of the geopolymer used are designed according to application. A range of different geopolymers can be specified for each individual application.

The Specification has been written to create a simple and standardised framework for clients to use to procure expanding geopolymer works. It has been developed by a steering group formed by industry experts drawn from Client, Contracting, and Consulting organisations, and is intended to represent a balanced apportioning of the technical risks.

The Specification has clauses which have been developed to allow the use of well-established and emerging uses of expanding geopolymers, with each clause containing standard items which are always applicable (unless overwritten by the specifier) and project-specific headings which require input from the specifier. To this end, this document requires a Project Specification to provide these inputs. Direction on what is required for this is provided in the guidance notes.

This document is intended to be read by anyone about to embark on a project considering the use of expanding geopolymers regardless of the level of previous experience with expanding geopolymer technology.

Use of this Specification

Clauses required for all projects	1. General	2. Design
	3. Execution	4. Geopolymer material quality control
Application specific clauses	5. Improving load settlement response	6. Filling voids and/or cavities
	7. Reducing leakage and/or permeability	8. Stabilising or lifting structures
	9. Treating shrinkage and swelling	10. Controlling real-time displacement
	11. Controlling liquefaction	12. Geopolymer columns

Figure 1 Specification map

This document is arranged in 2 main sections: an introduction to the specification which provides general guidance to assist with its successful use, and with the procurement of expanding geopolymer works in general; and the Specification, for incorporation into contractual information. Guidance notes to assist specifiers in using the Specification effectively are included throughout.

As depicted in Figure 1, Clauses 1 to 4 of the Specification contain general requirements which are considered applicable to all projects.

The following fields of application are also included within this Specification, but this does not prohibit the specifier from developing novel applications in partnership with an expanding geopolymer Contractor and adapting the appropriate clauses to fit that application. These method-specific clauses should only be completed for the method proposed for the project, and methods not used should be left blank.

Clause 5 – Improving load settlement response

Clause 6 – Filling voids and/or cavities

Clause 7 – Reducing leakage and/or permeability

Clause 8 – Stabilising or lifting structures

Clause 9 – Treating shrinkage and swelling

Clause 10 – Controlling real-time displacement

Clause 11 – Controlling liquefaction

Clause 12 – Geopolymer columns

Acknowledgements

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- Colin Edie (CECL Global)
- John Gannon (Byland Engineering)
- Richard Holmes (Geobear)
- Peter Ingram (Arup) (Chairman)
- Andy Kendall (HS2)
- Tuomas Lievonen (Geobear)
- Richard Sutherden (Murphy Group)
- Fred White (Arup)

Roles and responsibilities

Due to the specialist nature of the injection of expanding geopolymers, it is envisaged that most projects that are procured using this Specification will be carried out by a specialist Contractor. This document is therefore written with the assumption that it will be used by the employer (or more likely an Engineer working on their behalf) to specify performance criteria for the works (e.g. required post-treatment soil properties, or structure displacements, etc.).

Design of the geopolymer / injection arrangement / system to deliver the specified outcomes is assumed to be by a specialist Contractor. It is further assumed that the ground investigation will generally be supplied by the Employer, although probably in consultation with the specialist sub-Contractor.

Clearly this does not preclude this specification being used by designers with a strong competence in the design of such systems, but careful modification of clauses may be required to properly define responsibilities in such instances.

This Specification uses the terms ‘Employer’, ‘Engineer’, and ‘Contractor’, but these can be replaced as required to suit the particular contract under which the work is being procured.

Contract

This Specification does not constitute a contract, and therefore an appropriate form of contract must be entered into between the parties involved in order to set out their roles and responsibilities. Several off-the-shelf contracts (among others) are available including:

- The New Engineering Contract (NEC)
- The Joint Contracts Tribunal (JCT); and
- The International Federation of Consulting Engineers (FIDIC).

The Employer should consider which overarching contract best meets the overall needs of the project.

Competence

The Construction (Design and Management) (CDM) Regulations 2015 require that all parties to the contract must be competent, including the Employer.

For expanding geopolymer works it is important that the client selects professionals that are appropriately experienced in this type of work and should seek designers and Contractors that can demonstrate a successful track record in similar applications to those envisaged.

Temporary and permanent works

This specification applies to both permanent and temporary works which may be designed by different contractual parties and thus it is essential that these are coordinated and that all parties are aware of the design and construction of the project.

Many Geopolymer schemes will become part of the permanent works but may require careful consideration in the temporary state (e.g. when nearby excavations are present or planned).

In order to carry out the Geopolymer injection works the following items will require consideration:

- Service location, diversion and or reinstatement prior to, during and following the injection works.
- A suitably designed and constructed working platform from which the works are carried out.
- Prior removal of obstructions that impede the specialist works.
- Clearance around working positions and protection of adjacent works and third-party property to allow the injection works to proceed.
- Any pumping or drainage required to keep the site free of flooding, to allow the injection works to proceed.
- The provision of accurate setting out and levels with clearly defined datums and base lines.

Health, Safety & Welfare

The design and execution of the works must be carried out in accordance with the current requirements of UK law, or the appropriate requirements if the works are overseas. In the UK the Health and Safety at Work Act and the CDM regulations place specific requirements on employers, designers and contractors, to ensure that health and safety are considered at all stages of the project.

Risk management is the responsibility of all parties and each party shall undertake their own risk assessment of the Works.

- The location of all known services shall be clearly marked.
- The process involves the use of high-pressure hoses and fittings and a regime of daily visual checking of these along with a scheduled maintenance and replacement programme should be provided by the Contractor.
- The injection system needs to have inherently safe controls to ensure that liquid cannot be discharged at pressure in an uncontrolled manner. A system of 2 switches or handles that are engaged simultaneously before injection can commence along with a fail pressure relief system both for the pump and the injection gun.
- When handling the materials, the use of the correct PPE / RPE shall always be employed. Other non-working personnel should be excluded from the work area using physical barriers. When used in buildings, adequate ventilation shall be supplied.
- An assessment of the structure being worked on or adjacent to the works should be made to ensure that instability does not occur. As a minimum, a visual inspection, and a level and verticality survey should be conducted prior to the work and the use of rotating laser levels to monitor movements to within 1mm during the works.

Quality

To demonstrate that the designed and constructed works meet an appropriate standard of quality, it is important to control record keeping and workmanship. As a minimum, the employer should ensure that the designer and Contractor have appropriate quality management processes in place. In the UK a quality management system established in accordance with BS EN ISO 9001 is common.

The Contractor should demonstrate that the works are constructed to the required standard. This should be carried out by ensuring that appropriately qualified and experienced personnel are used to supervise works on site and by the keeping of appropriate records. This Specification provides minimum standards for these, and if required these can be supplemented in the Project Specification.

The design should include requirements for site verification, which is particularly important in expanding geopolymer applications. The record-keeping and supervision process should demonstrate that the required verification works are carried out.

Environmental and sustainability

The use of the geopolymer should meet the exemption criteria of Item 20 (j) (v) of *The Water Framework Regulations (2017)*.

The contractor should demonstrate that the materials being used in the works have been subject to an Environmental Impact Assessment and that the activity meets the requirements of Clause (b) of the *Environmental Permitting Regulations (2016)*, Schedule 22.3.3.

Tendering expanded geopolymer works

As stated above, it is envisaged that the majority of expanding geopolymer works that are procured using this Specification will be designed and constructed by a specialist Contractor. Employers should therefore aim to identify several Contractors with suitable experience of relevant works, or to work collaboratively with a single supplier to develop a suitable scheme.

The tender information should provide the specialist Contractor with all information required to design and construct the works, and the Contractor should highlight any information that they believe is missing or is additionally required with their tender return.

The tender should include details of all known site information and constraints relevant to the works, and would normally include:

- Desk Study information;
- Ground Investigation (appropriate to the envisaged works);
- Information about the need for the works, and any structures or other works that interact with the expanding geopolymer works;
- Information on existing third-party assets that may be impacted by the works; and
- Known constraints to the works.

The Project Specification should also contain details of any design codes or methods to be used, and performance criteria for the works.

Tender information supplied should be targeted to the expanded geopolymer works, and not contain irrelevant information. Much time is wasted by tenderers sifting through large volumes of information to find the relevant details, and this should be avoided where possible to reduce overall construction industry costs that are inevitably passed on.

The following technical documents would normally form part of a contract for expanding geopolymer works:

- Conditions of contract (and of subcontract where applicable);
- General and Project Specifications;
- Drawings; and
- Ground Investigation (including desk study) and topographic data.

Specification

All design, execution, and materials shall be in accordance with the appropriate British Standards, European Standards, codes of practice and other specified standards current at the date of tender.

Where there is any conflict of requirements in this Specification, the requirements of the Project Specification shall take precedence. Where there is any conflict of requirements of this Specification with any published standard, this Specification shall take precedence over that standard, but only for the part of the works to which the conflict applies.

GUIDANCE

Text shown in boxes is intended to provide guidance for specifier and contractor only and does not form part of this Specification.

1 General

1.1 Application

The introductions of each method specific clause describe appropriate soil conditions for the use of each technique in detail however, soils with the following characteristics shall not be treated without suitability assessment:

- Organic soils (mainly clays, silts and peats where organic content is more than 10% by mass);
- Soils with an average modified plasticity index, $I_p' > 40\%$; and
- Frozen ground.

1.2 Definitions

Table 1 Definition of terms used throughout the Specification.

Term	Definition
Engineer	The person or organisation responsible for specifying the Works. This could include those who may need to take on this role without being an Engineer e.g. Architect, Project Manager or Agency
Contractor	The specialist expanding geopolymer contractor
Employer	The organisation engaging the Contractor e.g. Main Contractor, Developer, Asset owner and/or Operator, Insurance Company, Homeowner
Works	The permanent expanding geopolymer construction

1.3 Project Specification

The following matters, where appropriate, shall be described in the Project Specification:

A. Person or organisation taking on the role of the Engineer.

B. Location and description of the site, including site datum and, if possible, site grid.

C. Objective(s) of the Works (including proposed method or Specification clause(s)).

D. Contract drawings.

E. Proposed programme for the Works.

F. Responsibilities (for Employer, design, monitoring, disposal of material etc).

G. Site investigation including geotechnical and geo-environmental information, and the need for further work.

H. Identification of underground utilities/services and other existing structures.

I. Any previous repair, remediation, or improvement works carried out.

J. Any other technical requirements.

> GUIDANCE
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> Contract drawings (Item D above) should include, as a minimum, a scaled plan and section through the works highlighting any known design and construction risks. Depending on the extent of design carried out by the Engineer prior to procurement of the expanding geopolymer works, these may also include a numbered schedule showing the injections and sequencing, and details of injection termination and verification criteria.

1.4 Health, Safety & Welfare

Every site should be suitably and sufficiently risk assessed (*The Management of Health & Safety at Work Regulations*, 1999), and this risk assessment conveyed to the operatives carrying out the work.

In addition to all current applicable Health, Safety and Welfare legislation, the following, not exhaustive, list of items specific to expanding geopolymer works shall be explicitly considered in the Tender:

- The identification of all underground utilities/ services and other existing structures. These shall be located before any ground is broken;
- Means of prevention of spills, accidental discharges, and the pollution of water courses, drains and sewers;
- The provision of adequately sized spill kits during the Works;
- Preventative measures (e.g. special breathing masks and equipment) when injecting in confined spaces, or where there are members of the public nearby;
- Operatives ensuring there is a suitable compression fitting on the injection tube to prevent accidental blow-offs; and
- Controlled use of any lasers to be used for monitoring movement of surfaces during the injection process, both in the selection of eye-safe equipment, and in the exclusion of non-authorised persons from the work area.

> GUIDANCE
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> The most frequent hazards associated with the application of geopolymers include, but are not restricted to:
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> - Damage and injury from striking buried services (gas, electricity, water, telecommunications, and drains, etc.). Refer to HSG47 for control measures. It is advisable to carry out a pre-work survey of drains in the vicinity of the injection zone, not only to locate their position but also to assess their condition. Drains that are in poor condition are vulnerable to the egress of expanding geopolymers and therefore may need to be repaired in advance.

- Hand Arm Vibration Syndrome from the use of drills over an extended period. Refer to The Control of Vibration at Work Regulations, 2005, for how vibration exposure should be managed. Typical controls include the use of personal monitors and restricted drilling times.
- Noise from drilling, especially when drilling into concrete. Refer to The Control of Noise at Work Regulations, 2005. In most cases this will involve selection of the right tools and equipment, and the wearing of correct PPE.
- Personal or environmental contamination from geopolymers, either in their liquid state (prior to reaction, when they are still a separate hardener and polyol) or in their reacted, cured, form. The Control of Substances Hazardous to Health Regulations, 2002, provides guidance on the storage, transport, and handling of materials such as geopolymers. COSHH assessment should be carried out and made available to all users so they are fully aware of all the controls that need to be followed.
- Discharge of VOCs and CO_2 at the point of injection. None of these gases are present in large quantities and they soon dissipate in outdoor or well-ventilated areas. However, caution should be taken when injecting in confined spaces, or where there are members of the public nearby, as additional preventive measures will need to be taken.
- The failure of pressure systems, particularly compressed air systems used in the delivery process. Refer to The Pressure Systems Safety Regulations, 2000.

In addition to the typical site specific hazards mentioned above, it is important for both safety and quality reasons to mention: (1) the duty under *The Health and Safety at Work Act,* 1974, for employers to provide all operatives with suitable and sufficient information, instruction, training and supervision in order for them to carry out their work safely, and (2) the duty under *The Provision and Use of Work Equipment Regulations* (PUWER), 1999, to ensure the safe use of equipment operated during the drilling and injection processes.

Although the cured geopolymers are not hazardous to the environment (as classified under the European Waste Code 170604), users are required by *The Environmental Protection Act*, 1990, to exercise a proper duty of care to ensure all reasonable steps are taken for the safe, and legal, management of waste.

Under the *Construction, Design, and Management (CDM) Regulations,* 2015, Principal Contractors on all construction sites, whether notifiable or not, should ensure the provision of adequate welfare facilities. In so far as is reasonably practicable welfare should include washing facilities and first aid, in case of accident or personal contamination.

1.5 Document submittals

Document submittals shall be as per the requirements of Table 2, or as stated in the relevant Specification Clause or in the Project Specification.

Table 2 Document submittals

Specification Clause(s)	Item	Timing
	Items required in the Project Specification	As stated in Project Specification
2.2	Geotechnical Design Report (GDR)	At least 2 weeks prior to commencing the Works
2.3	CV of proposed Designer	At Tender
2.4	Target mix design	At least 2 weeks prior to commencing the Works

3.2	Method Statement and Risk Assessment	At least 1 week prior to commencing the Works
3.3	Provisional execution programme	At Tender
3.3	Detailed execution programme	At least 1 week prior to commencing the Works
3.4	CV of proposed supervisor	At least 1 week prior to commencing the Works
3.5	Details of the Plant, Protection and Maintenance regime	At Tender
3.6	Drilling records	Within 24 hours of completing a bore
3.9	Process control system for injections	At least 1 week prior to commencing the Works
3.9	Post-construction surveys of any potentially impacted assets, including CCTV surveys of any buried pipes, sewers and drains in order to confirm they have not been contaminated with geopolymer.	Within 14 days of completion of the Works
3.9	As-built injection layout drawings.	Within 14 days of completion of the Works
3.9	Sample daily record sheet.	At Tender
3.9	Results of material tests, process control tests and equipment calibrations.	Within 2 days of completion of the relevant test or calibration
3.9	Results of validation tests.	Within 7 days of completion of the test
3.9	Reports produced on site in accordance with BS EN 12175: 2000 clause 10.2	Daily during execution
3.9	Proposal to remedy a non-conformance	Within 7 days of discovery or receipt of the Engineer's request for further information

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If different time periods for submittals to those stated in this Specification are required by the specifier in order to suit particular project requirements, these should be specified in the Project Specification, with reference to the relevant clause requirement that they are replacing.

1.6 Ground investigation and conditions

The Contractor shall report immediately to the Engineer the discovery of any variation in ground conditions from those reported in the site investigation which will impact the site works or the validity of the design.

The Contractor's design submission shall include a statement as to whether the ground investigation provided by the Employer is adequate, or whether further investigation is required to verify design assumptions.

1.7 Installation tolerances

Table 3 lists minimum installation tolerances. These general tolerances shall be adopted unless other tolerances are stated in the Project Specification of the method specific clauses.

Table 3 Tolerances

Definition of injection	Tolerance
Positioning of injection points	+/- 100mm
Monitoring accuracy for vertical movements	+/- 0.5mm
Inclination of drill string or injection tube before entry into the ground	+/- 2.5°

1.8 Proximity limits

The Contractor shall determine, through consultation with the relevant asset owners, the agreed proximity limits to their assets and if applicable, obtain the relevant concessions. These agreed proximity limits shall be proposed to the Engineer prior to commencing the Works. The Contractor shall consider the limits throughout the drilling and injection operations.

The Contractor shall consider the proximity to drains and other voids and state in the tender return the mitigation measures available should the geopolymer commence filling them.

1.9 Quality management

The Contractor is required to work to a Quality Management System (QMS) established in accordance with BS EN ISO 9001. Details shall be provided prior to commencing the Works on site.

The Contractor shall demonstrate appropriate documentation for the product and processes.

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British Board of Agrément (BBA) accreditation may be a way for the Contractor to demonstrate their adherence to a QMS. The accreditation could assist with demonstration that the contractor's systems have been assessed by an independent body as being appropriate.

2 Design

The Contractor shall include with the Tender a list of any missing information or additional information required to carry out the design of the geopolymer works, or if the targets set out for the Works are unachievable or unrealistic even with extra information.

The responsibility for the design of any required working platform or other temporary works required for access shall be with the Contractor, unless otherwise stated in the Project Specification.

The Contractor shall provide a schedule of attendance and any requirements for temporary works (including requirements for any Working Platforms to be designed by others), which do not form part of their design, with the Tender.

2.1 Project Specification

The following matters, where appropriate, shall be described in the Project Specification:

A. design standards and criteria (including geotechnical category and design life).

B. structural assessment (including a description of any existing structural assessment with record of damage and/or request for Contractor to carry out work).

C. requirement for a trial.

D. the responsibility for the design of any required working platform (if not by the Contractor) or other temporary works.

E. any other technical requirements.

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Item C is for specifying a trial of the proposed method to demonstrate its use, if required. For example, consideration should be given to the specification of a trial where the outcome of the injections is particularly critical, where there is concern about the impact of the geopolymer injections on third parties or other items not intended for remediation, or where new methods or materials are proposed.

2.2 Geotechnical Design Report (GDR)

The Contractor shall provide full details of their design within a Geotechnical Design Report (GDR).

For geotechnical category 2 and 3 projects, the GDR shall include the following items as a minimum and should, where available, cross-reference the Ground Investigation Report (GIR) and any method-specific requirements.

- a description of the site and surroundings;

- a description of the ground conditions;
- a description of the proposed execution;
- design values of soil and rock properties, including justification, as appropriate;
- a list of codes and standards applied;
- statements on the suitability of the site with respect to the proposed execution and the level of acceptable risks;
- geotechnical design calculations to demonstrate that the proposed scheme or methodology is appropriate;
- statements on whether the flow rate, volume, or mass of geopolymer is the control method for injection at each location, and all other important factors related to injection including tube extraction speed;
- drawings (including layout plan(s) and section(s) showing surface position, inclination, length, and number of injection tubes, sequence of injections, minimum clearances to structures/ 3rd party assets/ utilities, relevant Health, Safety, Welfare and Environmental information, and if applicable, the part of structure being treated);
- a plan of items to be checked or verified during execution or requiring maintenance or monitoring. Process control parameters shall be listed (the ultimate parameter intended to be measured shall also be stated) and range design values given (give ranges in guidance 50% to 200%, investigate large variations outside of these brackets); and,
- a statement as to whether there is a requirement to carry out a trial to validate the design if not required explicitly in the Project Specification.

For geotechnical category 1 projects, lesser requirements apply to the GDR and the project specification should list reduced minimum contents as appropriate.

Where additional ground information is required either to complete or verify their design, the Contractor shall state this with the tender, and propose appropriate further geotechnical investigation.

2.3 Competence

The Contractor’s designer shall be appropriately experienced in this type of work and the Contractor’s design team shall include as a minimum one qualified engineer with at least 10 years of design experience in geotechnical works or geopolymer ground engineering. A curriculum vitae of the proposed designer shall be provided with the tender.

2.4 Injection

Injection points shall be designed so as to limit the potential for volume loss cause by differences in the drilled hole diameter and the injection tube diameter.

The Contractor shall specify the target mix design and present the design characteristics of the proposed fluid mix in the GDR including:

- colour;
- density;
- maximum injection pressure; and
- temperature.

Based on BS EN 1997:1: Eurocode 7, the following requirements shall be met before injections are started:

- Acceptable limits of behaviour shall be established;
- the range of possible behaviour shall be assessed, and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits;
- a plan of monitoring shall be devised, which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage, and with sufficiently short intervals to allow contingency actions to be undertaken successfully;
- the response time of the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system;
- a plan of contingency actions shall be devised, which may be adopted if the monitoring reveals behaviour outside acceptable limits.

As a result, the designer shall define the expected limit conditions of the geopolymer treatment and highlight the most likely scenario. While executing the treatment, a monitoring system shall be installed to assess the evolution of the target data. The designer shall indicate the actions to be adopted for the different monitoring results which may occur.

The injected material shall retain its volume and strength over time without impacting the treated soil/structure. The number of times the geopolymer is injected, the composition of the geopolymer, its characteristic free rise density (that is, its density under free atmospheric pressure without confinement) and set compressive strength shall be stated.

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Consideration needs to be given, inter alia, to the type of soil the geopolymer is injected into, the long-term stresses it is required to sustain, its likely in-situ density (and related properties) and its time dependant mechanical behaviour at ambient stress levels.

Where geopolymer is injected into fine soils through hydrofracturing, some stress relaxation is likely to occur as the soil consolidates and repeat injections may be required.

The minimum required characteristic set geopolymer compressive strength and / or stiffness modulus need to be considered in relation to the intended application. Generally, where the compressive strength of the set geopolymer exceeds 4 times the mean ground stress, creep will be negligible.

Creep calculations can be performed where the time dependent stiffness modulus values are known. Geopolymer manufacturers can provide mechanical properties including data from creep tests to determine the long-term stiffness modulus decrease.

Lower strength and stiffness geopolymers are usually satisfactory in void filling applications. Higher strength and stiffness geopolymers are necessary where there is sustained heavy foundation loading for example under massive ancient masonry foundations or where geopolymer inclusions (sometimes known as Geopolymer columns – see Clause 12) are used. For some applications, the strength and stiffness of the geopolymer is of secondary importance for example where densification of the soil is the primary treatment objective.

2.5 Drill hole diameter

The drill hole diameter should be as small as is practical to enable injection tubes to be inserted and expanding geopolymer to be injected at the required level.

The Contractor shall propose for acceptance the following in the GDR:

- Method of hole formation, hole diameter, inclination and length;
- Injection tube numbers per drill hole and their diameter and length;
- Injection depths required;
- Injection sequence – ascending or descending; and
- Need for repeat injections.

3 Execution

Execution should follow the principles of BS EN 12715:2000 Execution of special geotechnical work – grouting, suitably adapted to geopolymer injection work.

3.1 Project Specification

The following matters, where appropriate, shall be described in the Project Specification:

A. working area and requirements for temporary works (working platform) suitable for installation (including whether work is permitted inside and outside the structure).

B. execution sequence and interfacing works.

C. installation tolerances and responsibility for measurement.

D. management of the environment (incl. noise and vibration, working hours, pollution control, contamination, impact on groundwater regime).

E. asset protection.

F. reinstatement of injection holes.

G. permissible working hours.

H. other technical requirements.

3.2 Execution method

The Contractor shall submit with the tender an outline of the relevant details of the method of geopolymer injection, and the relevant details of the plant and monitoring equipment to be used. A Risk Assessed Method Statement (RAMS) with an Inspection and Test Plan (ITP) shall be prepared and submitted for acceptance at least 1 week prior to commencement of the works which inter alia includes consideration of:

a) Management and supervision
b) Identification, location, diversion, marking and protection of buried and overhead utilities / services.
c) Pre-construction surveys, including by CCTV, of buried pipes and drains which may be impacted.
d) Required construction sequence e.g. top down or bottom up injections, hit one miss one injections etc.
e) Equipment and methods to survey building(s) during injections to ensure structure movements caused or induced are as required.
f) Method of drilling
g) Method of geopolymer preparation and placement

h) Records to be kept of samples taken, examinations made, tests carried out and injection volumes achieved.

The Contractor shall submit with the tender all relevant details of the method(s) proposed for dealing with manmade and natural obstructions and voids.

The Contractor shall carry out the work in such a manner as to comply with current environmental legislation and the noise and vibration limits stated in the Project Specification.

3.3 Execution programme

The Contractor shall submit a provisional programme for executing the works at the time of tender and a detailed final programme at least one week before commencing the works.

As a minimum, the provisional programme shall contain the following:

- Overall duration of the Works
- Testing and verification times
- Basic resourcing levels
- The key dates for completion of various parts of the works
- Time periods allowed for further ground investigation, design of injection works, design and construction of temporary works, construction of Works

As a minimum, the detailed final programme shall contain the following:

- Linked date-based activity bar chart to include all items in tender programme and with Works construction operations broken down into drilling, injection, validation and reinstatement operations
- Starting date, access date, Key dates and completion date.
- order and timing of all operations planned to do the Works.
- order and timing of works by others to enable the contractor to achieve the overall programme.
- Float, Time Risk Allowance, health & safety requirements.
- Plant, materials and other resources
- Required periods for approvals.

Any restrictions on permissible working stated in the Project Specification shall be adhered to.

3.4 Supervision of the Works

The Contractor shall provide a full-time competent supervisor on site to be responsible for the execution aspects of the works.

This supervisor shall be experienced in the proposed method. A curriculum vitae of the proposed supervisor shall be submitted to the Engineer at least one week before commencing the works.

The injection operation team shall include as a minimum one senior technician with a minimum of 5 years of geopolymer injection experience.

3.5 Plant and equipment

All geopolymer grouting plant and equipment shall be of a type, capacity, and mechanical condition suitable for carrying out the work. They shall be compatible with the chemicals being injected and shall be maintained in the appropriate operating condition at all times during injection.

The geopolymer injection equipment must include at least two of the following:

a) Specified proportional components for volumetric capacities for each base material
b) Specified mixing module to ensure adequate mixing of geopolymer components
c) Purpose built in-line mixer, for example - carrying out far end mixing applications

For sites where injection is time-critical, such as real-time settlement mitigation, back-up injection capacity shall be provided and maintained in operating condition at all times.

All equipment for control of pressure (of each component as delivered to the nozzle), flow, and temperature measurement shall be calibrated every 6 months, and the calibration certificate held on site for inspection. Equipment shall be subject to periodic site calibration at an appropriate frequency throughout the works.

The contractor shall provide details of their Plant, Protection and Maintenance regime, including proposed site calibration frequencies and methods with their Inspection and Test Plan (ITP).

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The ITP should describe the mode and manner of inspection, testing and checking the correct functioning of the machines / equipment. Including:

- Visual check that nozzles are clear and unobstructed
- Check by measurement that proportions of the 2 parts making the geopolymer are supplied to the mixing nozzle in the correct quantities
- Check that the mixed liquid geopolymer of at the correct temperature
- Visual check that colour of the geopolymer is consistent and correct through comparison to a standard colour chart or other accepted and approved methods.

3.6 Drilling

Drilling crews shall be fully briefed in accordance with a task-dedicated risk assessment of any potential hazards or obstructions which might impact upon or arise from the drilling operations. All injection works shall comply with the Method Statement and the Contractor’s design.

The Contractor shall record and submit drilling records in accordance with BS EN 12715 Section 10.3 within 24 hours of completing a bore. As a minimum, these shall contain the following:

- Hole number;
- Diameter of hole;
- Depth drilled;
- Declination angle drilled;
- Date drilled;
- Time to drill the hole;
- Type of drill and bit used;
- Method of drilling;
- Type of drilling fluid, if any;
- Note of any sleeving or casing required and depth of same;
- Name of drilling operative;
- Record of material / strata drilled noting depth changes of each material if known;
- Record of any voiding and depth of same;
- Presence of any obstructions and record of time taken to drill the hole;
- Number, diameter (inside and outside) size and length and material of injection tubes; and
- Type, location and material forming seal to prevent leakage or constrain outflow of geopolymer.

GUIDANCE

All the holes should normally be prepared by using manual electric rotary-percussion drills. If additional injections for ground improvement are planned in the same locations with multiple tubes, diamond coring can be used for larger diameter holes. Any of the used drilling methods should be so designed to not transmit vibrations to the structure and should enable work to be carried out in limited spaces if required. Typical injection hole diameters used are 12 to 26 mm. Larger hole diameters can be used for installing multiple tubes or for geopolymer columns. Smaller hole diameters down to 6mm can be used for tiled paving.

Where lifting is the aim, all holes must penetrate entirely the structure to be lifted.

The length of the drill bit should be selected according to the structural requirement (material, thickness and reinforcement). Extensions can be used to reach deeper drilling holes and according to ground improvement drilling guidelines.

Drilling of holes will need to provide coverage of the whole area to be treated. In the case of limitations on top of any pavement, holes can be drilled with an angle or horizontally, in order to ensure the material can be injected into the selected zone. The executed hole locations should follow the designed grid spacing and clearance between individual points.

3.7 Injection

No injection shall commence unless:

- An accepted design is in place;

- Clear limits have been agreed and set for the allowable building/asset displacements (e.g. total settlement, slope, deflection, heave), and the injection team is fully briefed;
- The Method Statement has been accepted in writing by the Engineer;
- A suitable and adequate monitoring system is in place and is fully functional and baselined;
- The programme and sequence have been accepted in writing by the Engineer; and,
- An adequate management / control system is in place with key responsibilities identified.
- Material performance has been verified – refer to Clause 4.3

The Injection tube diameter shall follow the requirements of the design, which shall be intended to reduce volume loss of soil into the injection holes.

Injection progress shall be reviewed daily and shall be modified as required by the design to reflect available monitoring data, and an analysis of structure displacement trends (where applicable), current monitoring data, and allowable limits. This review shall consider whether any trends are likely to impact the execution programme.

After completion of all injections, and when the targeted levels are reached, the injection tubes shall be cut off at the ground level or pulled out (or as required by the Project Specification 3.1F).

On completion of the Works, injection holes shall be backfilled in accordance with EA regulations. Where boreholes pass through structural elements or foundations, holes shall be reinstated in accordance with the Project Specification (3.1F).

GUIDANCE

For ground improvement projects, predicted results or impacts for the ground should be assessed by geotechnical calculation or modelled by use of one of the following; FEM, cavity expansion theory or with other adequate design software.

Typically, individual tubes with 6-12 mm outside diameter metal tubes are used with min 1 mm wall thickness.

The length of the injection tube is selected firstly according to any structural thickness requiring penetration, and secondly the treatment depth. For usual pavement structures the main purpose of the tube is to allow material delivery from the injection mixing chamber into the tube and further into drilled installation holes. The top of the tube needs to be left about 100mm above the level of the injection platform to allow connection with the injection mixing chamber. If additional ground injections are required, the longer lengths may be required. As an alternative to individual tubes, pre-installed injection packers can be used.

3.8 Verification

Verification for individual methods is considered in the appropriate method-specific clause (Clauses 5-12).

3.9 Records

A process control system shall be established (and submitted to the Engineer at least one week prior to commencing the works) to manage the injection programme to allow for systematic, time-referenced, recording of material characteristics, mix volumes and pressures and building displacements, to ensure that these comply with the specification/design limits.

In addition to the above, the following shall be provided:

- Post-construction surveys of any potentially impacted assets, including CCTV surveys of any buried pipes, sewers and drains in order to confirm they have not been contaminated with geopolymer.
- As-built injection layout drawings.
- Sample daily record sheet.
- Results of material tests, process control tests and equipment calibrations.
- Results of validation tests.
- Reports produced on site in accordance with BS EN 12175: 2000 clause 10.2

If any part of the works is discovered or suspected not to conform to the Specification then the Contractor shall, within seven days of discovery or receipt of the Engineer’s request for further information, notify the Engineer of their proposal to remedy the non-conformance or verify that the work done meets the requirements of the Specification.

4 Geopolymer material quality control

4.1 Material quality

Manufacturing of geopolymer base component materials shall comply with ISO 14001, ISO 50001, ISO 17020 and ISO 17025 certifications.

Where required to prove the suitability of geopolymer material use in a selected application, the Contractor shall provide the relevant test certificates.

The Designer should specify the performance requirements that are to be achieved of the material and or the composite and the contractor shall adequately demonstrate that their selection of materials meets these requirements. The list of properties shown below shall be considered depending upon application.

- Environmental impact assessment
- Effect on ground water quality
- Compressive strength and E-Modulus
- Chemical resistance
- Thermal resistance
- Insulation properties
- Durability
- Water absorption
- Biological degradation

The Contractor shall confirm that they have verified that the material from the manufacturer has been tested against its performance criteria.

GUIDANCE

British Board of Agrément (BBA) accreditation may be a way for the Contractor to demonstrate suitability of their equipment and material and methodology for use. The accreditation could assist with demonstration that the proposed system has been assessed by an independent body as being fit for its intended use provided it is installed, used and maintained as set out in the Certificate.

4.2 Quality checks

The contractor shall clearly state what quality checks they carry out in order to ensure that the selected solution will fulfil the requirements of the Specification. When considering the checks the following non exhaustive list shall be utilised.

- Shelf life of the material
- Storage / handling conditions
- Material processing temperature
- Reaction Profile

- Mix design
- Material consistency

4.3 Material performance verification

The contractor shall verify that the project specific material properties will comply with designed specifications and the manufacturer's technical data sheet (TDS) or certificate of analysis (CoA). The material properties shall be tested before project specific injections to verify the targeted performance, including the following:

- Free rise density after curing (Density at free atmospheric pressure)
- Reaction profile with;
    - Cream time
    - Gel time
    - Tack free time

Where required, the additional mechanical properties can be tested from the injected samples. The specific test and the sample sizes shall comply with the relevant test standard for rigid cellular polymers and to be executed in accredited test laboratories.

> GUIDANCE
>
> Refer to Clause 4.1 for details of certification and documentation of manufacturers properties.

4.4 Material characteristics

Geopolymers are used widely in various applications. The application specific requirements will determine the important properties of materials. The following table describes the most critical material characteristics for each application in order to help designers to take into account the relevant properties.

Table 4.1 – critical material characteristics per application

Clause No.	Clause Title	Reaction Profile (1)	Liquid viscosity	Volumetric weight (kN/m^3)	Compressive strength (MPa) (2)	E-Modulus (MPa)	Free Rise Expansion Ratio	Expansion pressure (kPa)	Permeability	Creep	Shrinkage
5	Improving load settlement response	X	X		X	X		X		X	
6	Filling voids and/or cavities	X		X	X	X	X	X			X
7	Reducing leakage and/or permeability	X	X						X		
8	Stabilising or lifting structures	X	X	X	X	X		X		X	
9	Treating shrinkage and swelling	X	X					X	X		
10	Controlling real-time displacement	X	X					X			
11	Controlling liquefaction	X	X		X	X		X	X		
12	Geopolymer columns	X	X		X	X		X		X	
Notes: (1) Reaction profile incl. cream time, gel time and tack free time, (2) Specify: Treated matrix or geopolymer											

GUIDANCE

Expanding geopolymers belong to the closed-cell rigid polymer group. Geopolymers are multi-component structural thermo-set polymers. Geopolymers are produced as a result of an exothermic polymerization of base component mixture in specific volumetric proportions.

The multi-component material comprises as its main base components a resin and a reagent/hardener to generate an expansive structural geopolymer grout. The mix of individual components and temperature settings are managed on site by a calibrated pumping and heating system in accordance with manufacturer’s instructions.

As a result of free expansion without confinement, the geopolymer volume can increase more than 30 times relative to its initial liquid form.

The volumetric mass of the mix in liquid state is around 1100 kg/m^3 and almost comparable to that of water (1000 kg/m^3). Expanded geopolymer on the other hand is characterised by significantly lower density dictated by the swelling pressure. After chemical reaction of the mix, the geopolymer forms a stable thermo-set, non-biodegradable and non-pollutant rigid polymer with a cubed weight typically ranging from 0.7 kN/m^3 to over 3.5 kN/m^3 depending on the state of containment. It is possible to achieve final densities of the geopolymer over 6.0 kN/m^3 in certain soil and structural conditions. Typical material technical specifications are presented in the table below.

Material specification	Typical value
In situ density	50 kg/m^3 – 500 kg/m^3
Compressive strength	0.5 MPa – 15 MPa
Shear strength	0.5 MPa – 3 MPa
Tensile strength	0.5 MPa -8 Mpa
Expansion force	Up to 10,000 kPa

The ITP should describe the mode and manner of inspection, testing and checking the correct functioning of the machines / equipment. Including:

- Visual check that nozzles are clear and unobstructed
- Check by measurement that proportions of the 2 parts making the geopolymer are supplied to the mixing nozzle in the correct quantities
- Check that the mixed liquid geopolymer of at the correct temperature
- Visual check that colour of the geopolymer is consistent and correct through comparison to a standard colour chart or other accepted and approved methods.

The MQT’s

- Schedule of samples of geopolymer and tests that are to be performed on it. Consider sample number, type, size, location, contained, storage procedures.

Regular Material Quality Tests (MQTs) should be conducted, concerning the injectors (including injection nozzles) and the quality of the expanded geopolymer. The inspections should be made at the beginning of every work shift and after any period of pumping activity. The inspection should include checks on compliance of pressure and temperature requirements of the injection system, and a visual inspection of polymerisation (in the open air) of the geopolymer mix (colour, texture, reaction profile etc.), before implementation.

The specific equipment that ensures proper mixing of the base products (proportioning, temperature, volume of material, pressure, etc.) should be checked at least once a month. The remaining equipment should be inspected according to the manufacturer's maintenance programme, or a minimum of at least once a year.

5 Improving load settlement response

All materials and work shall be in accordance with Clauses 1 to 4 of this specification.

5.1 Introduction

This clause provides requirements for improving or modifying the ground mechanical properties to achieve either: an increase in its ability to bear load, such as increasing its shear strength; or enhanced settlement characteristics, by improving its stiffness.

These two applications are fundamentally very similar however, the differences lie in how each method is verified.

This technique can be used to improve soils beneath existing structures (where physical resetting of previous ground movements is not required (e.g. Clause 8 would be more appropriate in that instance) or to improve soils prior to construction. The treatment of specific layer(s) and/or zone(s) can be identified by either the Client or determined by the Specialist Contractor.

Improving the stiffness and/or strength of a soil is usually achieved through injection at depth but may also be combined with shallow injections to fill voids depending on site-specific requirements. Where the latter only is applicable, Clause 7 should be used.

GUIDANCE

With regards to surface improvement, the selected geopolymer will be injected into the shallow soils directly beneath the formation level of the overlying structure/foundation, with the intent of fully re-establishing contact between the underside of the structure/foundation and the underlying soils by filling any voids present within the soil to be treated.

At depth improvement relates to soils being treated at greater depth and thus most concerned with the forces induced by loading. The objective of at depth treatment is to consolidate/compact the soil via:

- Elimination of voids by filling and compressing surrounding soil
- Expulsion of air and water
- Agglomeration of the soil (in cases where coarse grained soil is present)

Once injected, the geopolymer moves and expands both horizontally and vertically to a region that allows the material to take the path of least resistance, and thus has the greatest need to be reinforced. Once this has taken place, the geopolymer will expand, which will result in pressure being placed upon the surrounding soils resulting in densification, and ultimately an upward force being placed on the underside of the overlying structure/foundation.

Tensions and deformations induced by volumetric reduction of soil below buildings and/or other types of structures using geopolymer injections, are generally controlled by moving the soil in situ caused by the kinematics of the hydrofracturing of fine-grain soils.

Injections are typically performed within a normally consolidated soil (over consolidation ratio, OCR = 1, coefficient of lateral earth pressure at rest, $K_0 < 1$), initially characterised by horizontal geostatic tensions, that are less than the vertical ones. The first stage of treatment gives rise to hydrofracturing, mainly in a vertical direction. The expansion of the geopolymer within the vertical discontinuities increases the aperture. The expansion of the geopolymer also brings about an increase in horizontal tensions with a consequent reversal of the direction of the main tensions within the surrounding soil.

As a result of the rotation of the main tensions, by injecting additional geopolymer at a later stage at the same volume of soil, we can cause the aperture of a further series of fractures characterised, during this second stage of injection, by a prevalently horizontal direction. The aperture of the horizontal fractures lifts the foundation and recovers the settlement of the structures above.

Ground improvement to control settlements with geopolymer injection is applicable in most coarse and fine-grained soils, but must be verified for suitability by the geopolymer specialist Contractor, when:

Soil plasticity index PI-value > 40

Liquid limit > 60

Activity index AC > 1.0

5.2 Project Specification

The following matters, where appropriate, shall be described in the Project Specification:

A. Nature of site to be treated (under foundations or not under foundations).

B. Whether an improvement in strength or stiffness is required.

C. The target improvement values.

D. Treatment zone, if applicable.

E. Treatment verification methodology.

F. Other technical requirements.

GUIDANCE

For item C, these could typically relate to parameters such as ϕ' or Young's Modulus.

For item D, it is often the case that the Engineer would specify that the Contractor should determine the treatment zone.

For item E, typically DPTs or CPTs for strength or CBRs or PLTs for stiffness could be specified.

5.3 Design of geopolymer injection

The Contractor shall include in the GDR statements demonstrating that the following matters have been considered:

1. The design of the system to achieve the specified parameters or performance, including consideration of spacing, sequencing, levels, durations and volumes of injections, choice of material, and design life;
2. The impact of the injections on existing structures;
3. Proposed method of verification; and

4. Calculations demonstrating the expected future performance.

The Contractor shall design the injections to maximise the grouting efficiency and avoid the unnecessary loss or use of injected material.

The application specific material properties for expanding geopolymer are listed in Clause 4.3. If the Contractor proposes values for properties that are outside of the ranges stated, then they shall provide justification in the GDR.

5.4 Execution

No method specific execution requirements identified – refer to Clause 3.

5.5 Verification

Verification of the treatment shall be carried out over the whole area of works.

Both pre and post verification shall be carried out.

When comparing measurements, results shall be taken at the same location and using the same method. The minimum number of tests shall be 1 test for every $50m^2$ or if smaller area then a minimum of 1 test.

The Contractor shall carry out geopolymer injection until the point at which post-treatment verification measurements demonstrate the target values have been achieved.

If the target values are not achieved once all planned injections are carried out, the Contractor shall plan additional works to achieve the targets. The proposed works shall be submitted to the Engineer for acceptance.

GUIDANCE

For verification, due to the nature of grouted ground the taking of cores is not considered ideal and the use of dynamic probe testing or CBR testing should be done.

If Dynamic Probing is to be used then Super Heavy Dynamic probing should preferably be used as lighter probing methods may give false readings.

6 Filling voids and/or cavities

All materials and work shall be in accordance with Clauses 1 to 4 of this specification.

6.1 Introduction

This clause provides requirements for filling voids and cavities.

A void or cavity may be of man-made or natural origin. This might include, but is not limited to, solution features, historic mining activity, disused utilities or underpasses, and voids caused by erosion from groundwater flow around structures.

The nature of the injection allows for easy and precise access, without impact to the surrounding constraints. Expanding geopolymers can be an efficient material for these problems as the reaction of the combined ingredients causes a volumetric expansion of the material itself.

Where specific characteristics or properties are required from the site post treatment (e.g. complete void filling, structural characteristics, no permeability, reuse of void) a geopolymer can efficiently and reliably be used.

GUIDANCE

The minimum mass of the geopolymer required to fill a specific cavity/void should be based on the free rise density of the geopolymer.

The temperature of the cavity being filled should be measured prior to the injection in order to assess the potential long-term shrinkage impact of the geopolymer injected.

6.2 Project Specification

The following matters, where appropriate, shall be described in the Project Specification:

A. Nature of void or cavity (e.g. confinement, man-made or natural, presence of groundwater, ground gas or loose material, and existing surrounding temperature).

B. Existing assessment of the void or cavity including structural stability.

C. An assessment of safe access within the working area identified in Clause 3.1 A.

D. Known constraints including third-party assets.

E. Treatment verification methodology and required filler material properties.

F. Future foreseeable loading regime and use of treated area including further construction works directly affecting the filled material.

G. Other technical requirements.

6.3 Design of geopolymer injection

The Contractor shall consider the sequencing of injections such that the entire void may be filled, and a build-up of excessive air pressure, temperature and steam are not allowed to develop. If there are any specified constraints, the Contractor shall demonstrate how the works will not impact them within the GDR.

The Contractor shall consider the use of additional inert filler material, such as lightweight gravel. If additional filler materials are used in the void or cavity filling works, the Contractor shall demonstrate why this decision has been made and provide the material properties within the GDR.

The Contractor shall carry out their own assessment of third-party assets which treatment of the void or cavity may impact. If they identify additional assets not already specified by the Engineer in Clause 6.2 Item E, the Contractor shall notify the Engineer and provide a mitigation strategy for acceptance. This mitigation strategy is to be agreed by the Engineer prior to commencing the works.

The application specific material properties for expanding geopolymer are listed in Clause 4.3. If the Contractor proposes values for properties that are outside of the ranges stated, then they shall provide justification in the GDR.

GUIDANCE

Sequencing of injections during the infill is likely to be determined by which Geopolymer will be used (more specifically the density of the infill material) and type of cavity to be filled. Sequencing of the infill shall consider any injection control measures in place, and shall produce the most efficient, safe way of completing any void filling works.

The first items which must be considered are the volume/shape/dimensions/locations of the cavity(ies) to be filled. This will dictate the whole design philosophy for the project as it will determine the site-specific project requirements. Once the details of the cavity(ies) are established (and therefore the volume of Geopolymer required), accessibility and required resources can be examined.

The project requirements will guide which Geopolymer is used to carry out the void filling. Required Compressive Strength of the infill material should be compared to the measured Compressive Strength of available Geopolymers, with the infill material chosen accordingly (the least dense possible should be selected in order to ensure the placed material is as sustainable as possible).

In suitable cases, Geopolymer can be combined with another material in order to fill a void. Typically, lightweight aggregate or granular fill material is used to firstly fill the void in question. Geopolymer is then used to permeate the placed aggregate/fill, filling voiding. The mechanism by which the void is filled then follows the principles of a Ground Improvement project in coarse grained soil.

6.4 Execution

If additional filler materials are being used, the Contractor shall outline the sequence and method of placing of this additional filler material, and how these works will impact the injection of geopolymer.

Throughout the execution, suitable monitoring shall be in place, both as an observational measure to assess the progress of the void filling (e.g. cameras), and where relevant, as a precaution to ensure undue force is not placed on the void perimeter. Depending upon the nature of the void to be filled, further monitoring may be required to ensure that Geopolymer is not lost through a discontinuity in the void perimeter (e.g. a crack in a pipeline).

GUIDANCE

Typically, depending on accessibility, extra filler materials are commonly blown or poured in prior to injection of geopolymer.

The issue of accessibility considers both access to the point of entry to the void, and access into the void if required. This will feed into RAMS production for the project, along with the design risk register. Items such as, vehicular access, modified injection units, MEWPS, safety harnesses, confined space requirements etc are considered at this stage.

Suitable trigger time (time spent continuously injecting) should be considered to ensure proper control of the operation. This will ensure that the effects of the Geopolymer during the polymerisation process will remain fully controlled. The amount of trigger time set for any given project should consider the output of the installation equipment to be used (to assess the amount of Geopolymer to be installed in one injection), the reaction profile of the Geopolymer (to ensure that the trigger time allows suitable time for the injected Geopolymer to polymerise before beginning another injection), the depth of injection (to ensure the injection tube can be removed if required prior to being secured in place by polymerised Geopolymer) and the proximity of any surrounding infrastructure (to minimise the risk of any undue pressure being exerted).

6.5 Verification

The Contractor shall carry out post-treatment verification and submit relevant as-built data to support the verification of the works, to be agreed by the Engineer.

If the target verification measures are not achieved once all planned injections are carried out, the Contractor shall carry out an assessment which demonstrates why the targets were not achieved and shall plan additional works to achieve the targets. The proposed works shall be submitted to the Engineer for acceptance.

GUIDANCE

An assessment should be carried out to ensure that the Contractor does not continue to inject geopolymer and unknowingly fill adjacent structures through an unknown pathway.

Verification should be carried out when possible using an Endoscopic camera in an adjacent hole in order to observe complete filling. In addition to this a cross check on the volume of expanded material (in the free rise state) should be made if the void volume was a known and of a fully defined quantity, for example filling a tank of set dimensions.

Where it is not possible to use the above method then other means of verification could be surface reaction (flicker) or a borehole drilled into the area and then a camera survey. The spacing of these survey holes should be designed with the nature of the void in mind. A higher frequency of testing should be used for irregular shaped voids and sporadically spaced voids.

7 Reducing leakage and/or permeability

All materials and work shall be in accordance with Clauses 1 to 4 of this specification.

7.1 Introduction

This clause provides requirements for using expanding geopolymer to control existing water flow and permeability problems, or foreseeable water flow due to construction works.

Geopolymers behave well in contaminated environments and can also be used as preventative containment of contamination. Although the application and purpose of the treatment will vary, activities associated with this are the same or similar.

Primarily, the geopolymer can be used either to treat the ground mass, where the polymer acts as a barrier, or to treat fissures, voids, faults or cracks in structures or the ground, where the polymer fills the channels allowing water flow.

GUIDANCE

Given the hydro insensitive characteristics of geopolymers, along with the compaction/consolidation of treated soil within the treatment area that will be achieved via the kinetic energy caused by the expansion of the injected material (thus densifying the soil and minimising pathways for water migration), treatment can be used to reduce the hydraulic conductibility of treated soils.

7.2 Project Specification

The following matters, where appropriate, shall be described in the Project Specification:

A. An assessment of the leaking asset or assets including predicted flow path.

B. A permeability and groundwater assessment including any specific investigation results such as piezometers, PSDs, pumping tests, down-hole geophysics, and rising and falling head tests.

C. Current state of water content and aspect of ground to be treated (I.e. fissures, entire soil mass, bedding planes).

D. Contamination information.

E. Nature and extent of future construction works and resulting predicted groundwater flow.

F. Treatment verification methodology and/or required ground/structure properties.

G. other technical requirements.

7.3 Design of geopolymer injection

The Contractor shall consider the existing assessment of the leaking asset or groundwater regime, and the geological and geometrical model provided by the Engineer to develop the injection scheme.

The Contractor shall select a geopolymer that is suitable against water or known contaminants.

In the case of future construction works such as excavations adjacent to the geopolymer works, the Contractor shall identify the requirement for suitable measures.

The Contractor shall carry out a feasibility assessment on whether the existing groundwater is able to be displaced by the injected geopolymer or requires pumping prior to injection.

The Contractor shall identify any secondary effects which impact the vicinity or adjacent structures either positively or negatively as a result of the treatment.

The application specific material properties for expanding geopolymer are listed in Clause 4.3. If the Contractor proposes values for properties that are outside of the ranges stated, then they shall provide justification in the GDR.

GUIDANCE

Geopolymer must not be thought of as providing any geotechnical support to excavations. Where applicable, further support must be provided (e.g. sheet piles or propping).

Application will determine viscosity, curing time, and expansion rate.

In applications concerning permeation control within the ground, an assessment must be made regarding the permeability characteristics of the existing ground conditions within the relevant area(s) subject to the proposed permeability control works. The assessment may consist of various methods of testing to be performed within the depth of ground to be treated as to gain an insight into the parameters exhibited by the relevant ground.

This determines if the injection works are aimed at reducing the existence of pore space within a soil or stemming an ongoing flow of water (for example, during an excavation). The layout of injection points will be dictated by the type of project. In projects where the aim is to reduce the permeability of a soil mass, geopolymer shall be installed throughout the entirety of the target area, minimising pathways for water migration via the expansion of geopolymer compacting the surrounding soil causing void space to be reduced or as a result of the geopolymer itself creating an impermeable barrier.

The project requirements and site-specific conditions will dictate the Geopolymer to be used to carry out the permeability control works. Variables such as rate of water migration and target injection depth both impact geopolymer specification, considering such site-specific conditions should allow a geopolymer with a suitable reaction profile & characteristics to be specified.

7.4 Execution

Where existing groundwater flow rates are high, the Contractor shall manage the control of waste geopolymer escaping the treated zone.

GUIDANCE

In order to prevent the geopolymer from escaping, water courses or channels can be boomed off. Any collected geopolymer should be disposed of as normal construction waste.

7.5 Verification

The Contractor shall carry out post-treatment verification to demonstrate the effectiveness of the works.

Observations and/or measurements of the rate of water ingress and of the hydraulic conductivity or permeability of the ground to water shall be made before and after treatment. If the method for carrying out these measurements or observations is not detailed in the Project Specification, then the Contractor shall propose a suitable method with the tender.

The measurement of hydraulic conductivity shall be made in-situ by a suitable method chosen from those described in BS5930 section 48 and the further standards listed therein.

If the target verification measures are not achieved once all planned injections are carried out, the Contractor shall plan additional works to achieve the targets. The proposed works shall be submitted to the Engineer for acceptance.

GUIDANCE

Where practicable, the pre-treatment and post-treatment observations and measurements should use an identical method. Generally, the simplest most convenient method available which takes due account of the condition of the confinement state of the aquifer, the ambient groundwater levels and pressures and the ease with which flow, pressure and water level can be measured, should be selected.

In some applications, a visual inspection may be solely adequate and measurements not necessary, particularly in temporary works applications where observed stemming of significant leakage is the only required verification of effectiveness.

In other applications, the drilling of boreholes (or possibly the excavation of a soakaway pit or trench) and the measurements of changes in hydraulic head or flow under constant head or under controlled injection pressures shall be carried out as necessary. The spacing of points of measurement depends on the locations, extent and magnitude of leakage, no rigid requirement can be generally specified, each project has to be considered individually. The adoption of a variable head test shall carefully consider the implications of raising or lowering groundwater pressures on local ground behaviour.

Where permeation of the geopolymer is used to reduce mass granular soil permeability, it may be possible to obtain large block samples of the soil before and after treatment. Sampling of uncemented sand to provide undisturbed test specimens at the in-situ void ratio is very difficult to achieve and is a non-routine specialist activity requiring particular equipment, care and experience. If such samples can be obtained before and after treatment, it is possible to use a laboratory permeameter or triaxial cell to measure permeability. Such sampling and testing will be exceptional and unusual.

Visual inspection of retained excavations, basements, shafts, tunnels and the like shall, where practicable, be made and the locations, extents and magnitude of water ingress recorded. A standard method of examination and a proforma for consistent recording of visual observations shall be used.

If discrete leakage flows are observed, for example through cracks or joints in tunnel and retaining wall linings, floor slabs or through steel sheet pile clutches, the flow rate shall be measured by suitable means over a representative period of time or until a minimum known volume of water is collected.

BS8012 section 5.2 gives some guidance on inspection and survey of existing structures. The ICE specification for piling and embedded retaining walls defines a water tightness assessment level (WAL) for embedded retaining walls. The definitions and concepts may be adapted for use here.

Permeation control within soils can be verified by methods such as pre and post works Falling and Rising Head Permeability testing or by flow measurements at constant head or elevated head (packer or slug tests). By comparing the results determined via the pre and post testing, a reduction in the permeability of the treated soils will be shown. Alternatively, where site specific conditions allow, an observational approach can be employed whereby injection works are carried out systematically until the desired result has been achieved.

Secondary effects of this treatment may result in improved soil strength characteristics.

8 Stabilising or lifting structures

All materials and work shall be in accordance with Clauses 1 to 4 of this specification.

8.1 Introduction

This clause provides requirements for stabilising and lifting misaligned structures or structures that have moved or are moving under loading.

Geopolymer is injected directly below the affected structure, and a chemical reaction causes the geopolymer to expand volumetrically. The resulting expansion pressure generates the force of the uplift, rather than the pressure of injection of the geopolymer liquid.

For coarse-grained soils, the stabilising or lifting is achieved by permeation of the material into the soil directly underlying the structure and the expansion of the geopolymer within the soil. For fine-grained soils, the stabilising or lifting is achieved by expansion of the geopolymer between the foundation and the underlying soil.

This clause assumes that the problem is not related to the deep underlying soils' inherent ability to carry the load, but simply that the foundations' load-settlement behaviour has been softer than expected. If investigations determine that the unexpected movements of the structure are related to an underestimation of soil strength in the original design, then a solution specified under Clause 5 may be more appropriate.

GUIDANCE

It is not appropriate to use expanding geopolymer to stabilise or lift structures where:

1. Foundation structure is fragile or damaged;
2. Foundation widths are less than 0.5m;
3. Foundation loads are greater than the lifting pressure of the expanding geopolymer;
4. Foreseeable foundation loads are greater than the compressive strength of the expanding geopolymer; and
5. The structure is piled, anchored or structurally tied.

When stabilising structures, the geopolymer injection is continued until the point at which it begins to lift the structure. Once this point is reached, it can be assumed that contact between the unstable structure and the bearing soil has been re-established and so the structure is re-supported.

When re-levelling structures, geopolymer injection will be continued past the point at which it generates uplift of the structure. The injections should usually be concentrated around the most settled or sunken areas, moving towards the least affected areas as the treatment progresses.

Misaligned structures typically need to be lifted back to their original position in multiple stages, rather than lifting all at once to avoid unnecessary increase of structural stresses. The injections are continued until the desired final level has been reached.

If no structural assessment has been carried out, the Engineer can specify that the Contractor carries one out in this clause.

The application of re-levelling structures requires utilisation of swelling pressure of geopolymer by chemical expansion reaction and hydraulic pressure must not be used to generate lifting pressure. The expanding material used for lifting usually comprises a rigid closed-cell structural geopolymer

Geopolymer material mechanical properties are dependent on the structure to be releveled and underlying ground characteristics. The strength of the cured geopolymer material is strongly dependent on confined pressure and the initial volumetric weight applied.

8.2 Project Specification

The following matters, where appropriate, shall be described in the Project Specification:

A. Use, type and dimensions of structure, including any available as-built information.

B. Current and foreseeable future design loads of the structure.

C. Any applicable limitations associated with stabilising or lifting the structure.

D. Treatment verification methodology.

E. Any historical monitoring data associated with the structures to be treated.

F. Any other technical requirements.

8.3 Design of geopolymer injection

The Contractor shall carry out appropriate settlement analysis considering the as-built and current position, and the underlying cause or causes of the settlements or instability of the structure, including the expected rate of further movements, and a prediction of their magnitude.

The Contractor’s design shall include consideration of whether the expansion pressure of the geopolymer is sufficient to counteract the existing and future loads and whether the required lifting targets are achievable.

The Contractor’s design shall include an assessment of the rate of expansion and sequence of injections (including an assessment of the maximum amount of lift in any one injection) of the geopolymer, ensuring that the injection scheme does not over-lift or over-stress the structure. This assessment shall consider the details of the existing foundation reinforcement etc., and any impact on known third parties.

The Contractor’s design shall consider the method of stabilising or lifting with respect to the soil type, in particular, the ability of the geopolymer to permeate the underlying soil, including any strengthening effect of the underlying soil related to either compaction or densification.

The Contractor shall identify the requirement for any future interventions (where, for example, the proposed geopolymer treatment will not treat the underlying cause of the settlement but simply maintains the asset within operational tolerances) within their design.

The application specific material properties for expanding geopolymer are listed in Clause 4.3. If the Contractor proposes values for properties that are outside of the ranges stated, then they shall provide justification in the GDR.

> GUIDANCE
>
> The injection scheme would generally be designed to start in the most sunken and settled areas to release stresses of overlying structures.
>
> Typical clearance of initial injections is usually 1.0-2.0m grid spacing.
>
> The grid spacing should not be less than 0.5m for unreinforced or thin, flat structures less than 150mm thick. For steel reinforced structures or structures greater than 200mm thick, grid spacing should not exceed 2.0m.

8.4 Execution

The Contractor's method shall be such that the injection point is cleared prior to a re-injection.

Real-time monitoring shall be carried out throughout the geopolymer injection to ensure lifting of the structure does not exceed the specified limits or constraints in the design. Where lifting is occurring over a large plan area, lifting targets shall be defined using grid area levels.

The levelling equipment shall be located at a distance far enough from the point of injection so that it is not affected by the works. The precision of the structural level monitoring shall be a minimum of ±0.5mm accuracy.

If the level targets at individual locations cannot be reached during the first round of injections, re-injections shall be carried out by using the same injection points where possible. These re-injections shall be undertaken by clearing the already injected injection channel with the help of mechanical drilling. The selected drill bit for mechanical cleaning should have a diameter less than the internal diameter of the injection channel used.

> GUIDANCE
>
> In the case of linear structures, such as walls, the monitoring can be attached along the wall. Proximity monitoring is recommended to be 2.0m from the injection location or at 2.0m centres along the linear structure.
>
> Primary areas and injection points for the first injection should be selected according to the preliminary level survey. Typically locations with the most differential movements or with highest amount of settlement should be selected.
>
> The lifting amounts and targeted levels will depend on the initial state of levels and rigidity of structure. Normally these independent injection locations must not be lifted more than 10 mm at once.

8.5 Verification

Verification of the treatment shall be carried out over the whole area of works. Where multiple stages of lifting are carried out, measurements shall be recorded by surveys pre and post-treatment to confirm the effect of each geopolymer injection. When comparing measurements, results shall be taken at the same structural survey location.

The contractor shall carry out geopolymer injection until the point at which post-treatment verification measurements demonstrate the target levels have been achieved.

If the target levels are not achieved once all planned injections are carried out, the Contractor shall plan additional works to achieve the targets. The proposed works shall be submitted to the Engineer for acceptance.

GUIDANCE

The targeted level and flatness requirements and tolerances shall be project specific according to relevant technical guidance. (For example, by using Technical Report 34: Concrete industrial ground floors. A guide to design and construction, or similar.)

The targeted level and flatness requirements including tolerances should not normally exceed the original requirements of the floor.

The verification method shall consider possible long term performance impact by external items such as soil related changes.

Buildings and other similar types of entirely re-levelled structures should be measured from outside, by using a minimum of 3 measurement points. Performance plan to be executed according to project specific requirements.

Suitable level measurement methods: Laser level, water level, 3D laser scanning, precise level, tilt monitoring.

Structural damage and limitations to be considered in cases where relaxation of the ground is possible.

9 Treating shrinkage and swelling

All materials and work shall be in accordance with Clauses 1 to 4 of this specification.

9.1 Introduction

This clause provides requirements for using expanding geopolymer injection to treat clay soils which shrink and swell.

Clay soils are susceptible to seasonal moisture content and volume changes. The volume changes manifest as shrinkage and cracking as the soils dry and softening and swelling as the soils wet. These variations lead to ground movements which damage foundations and structures in contact with the ground.

Seasonal soil moisture and volume changes typically occur up to 3m below ground surface but can occur up to 6m depth. The intensity and distribution of change is strongly influenced by climate and by the presence of trees and shrubs, the roots of which extract moisture from the ground to a considerable depth.

Treatment by expanding geopolymer injection should fill existing and induced fractures, fissures and shrinkage cracks to reduce mass permeability and to reduce the risk of future soil moisture and volume change and/or produce a perimeter curtain of geopolymer treated soil which presents a barrier to horizontal flow of soil moisture and discourages growth of tree roots towards buildings.

GUIDANCE

The occurrence of clay soil shrinkage depends on but is not limited to: soil composition; local groundwater conditions; and, the nature of past, present and future vegetation close to the building.

Plastic clay soils are very fine grained non-porous materials. Fluid flow in them is generally very slow and movement of expanding geopolymer occurs along discontinuities and not through the mass of the material. Expanding geopolymer barely mixes with the clay soil it is injected into and it does not significantly modify the intrinsic clay properties. Most but not all pre-existing cracks or fissures in the clay soil are filled with geopolymer. It tends to flow into and through the most easily accessible and widest cracks close to the point of injection. This means that if a treated clay is subsequently wetted, the un-filled cracks can accommodate some swelling of the clay material by closing. The key task of the network of geopolymer-filled cracks is therefore to create a barrier that prevents sufficient wetting of the clay from an external source to prevent future significant mass swelling to occur.

The movement of a shallow building foundation by more than its normal serviceability limit state can be caused by a variety of conditions. The investigation of the soil and the building structure must clearly identify the correct causes of ground and foundation movement so that the treatment programme can be properly determined.

9.2 Project Specification

The following matters, where appropriate, shall be described in the Project Specification:

A. The required depth of ground improvement.

Specific ground investigation results e.g. PSD, natural moisture content, liquid, plastic and shrinkage limits, undrained shear strength, swelling pressure and amplitude, and state of soil suction.

B. Ground and/or foundation movements that are either permitted or required to be induced during the ground improvement works.

C. Arboricultural assessment and any foreseeable removal and/or planting of moisture loving species.

D. Treatment verification performance criteria, including any requirements for excavations to uncover the treated ground and details of reinstatement.

E. Other technical requirements.

GUIDANCE

For item A, the treatment depth should extend at least to the depth of significant clay soil desiccation and the minimum depth required from considerations of soil volume change potential and the characteristic of vegetation within influencing distance of the foundations. The Engineer may refer to NHBC guidance 2019 Chapter 4 to assist with this.

For Item D, it is vital that the Specifier provides performance criteria for verifying that the treatment is successful, so that it is clear to the specialist contractor how the success of the Works will be measured.

9.3 Design of geopolymer injection

If not provided in clause 9.2 item A, the Contractor shall determine the required depth of the ground improvement. The Contractor may refer to NHBC guidance 2019 Chapter 4.

The Contractor shall use high mass density geopolymers.

The Contractor shall use close-centred injection points at no more than 1m spacing vertically and horizontally.

The application specific material properties for expanding geopolymer are listed in Clause 4.3. If the Contractor proposes values for properties that are outside of the ranges stated, then they shall provide justification in the GDR.

GUIDANCE

Subsidence damage may arise from sources of ground movement other than swelling or shrinkage of clay as given in BRE FB13:

- Compression of a soft soil layer due to normal foundation loading
- Soil erosion
- Soil softening
- Variations in ground water level
- Compression of filled ground
- Collapse of mine-workings or natural cavities
- Nearby construction works including excavations
- Frost heave
- Chemical attack
- Vibration

- Slope instability

The above sources of movement shall be either identified or excluded before an expanding geopolymer injection remediation programme is planned and implemented. Expanded geopolymer may also be used to address several of the above mechanisms.

For shrinkable clays, close centre hole and injection port spacings are used and therefore the geopolymer travel distance is not usually critical. The Contractor should therefore produce a geopolymer that produces low viscosity and lower permeability in order that crack-filling penetration is maximised and treated soil mass permeability minimised.

The compressive strength of the set geopolymer should be matched to that of the clay to be treated. High plasticity clays are typically over-consolidated with undrained shear strengths of 100 kPa to 300 kPa. For soils of this type, the target compressive strength of the geopolymer would typically be no less than 0.3 MPa to 0.9 MPa. The Contractor should state the required target values in the GDR.

9.4 Execution

Real-time monitoring shall be carried out throughout the geopolymer injection to ensure movement of the structure does not exceed the specified limits or constraints in the design.

In the absence of specified limits, the Contractor shall cease works when movement of any structures is detected and shall seek guidance from the Engineer.

GUIDANCE

It will be usual for structural repairs or strengthening to be required to buildings which have suffered subsidence damage. The requirement for repairs and the timing of their execution in relation to ground treatment needs to be considered and agreed between the various parties. It may be desirable to delay repairs and redecoration until building movements have been shown to be complete for a period of one year so that the remediated building experiences a full cycle of annual changes in soil moisture state.

Treatment of high plasticity clay soils in the UK should ideally be carried out in late summer or autumn when the soil moisture deficit reaches a maximum and shrinkage cracks are most likely to be present and open. The behaviour of the ground and structure should be monitored for at least 1 year after treatment before repairs to the building structure are carried out. Repeat injections may be necessary.

For treatment of shrinkable clays, hydrofracturing may be necessary.

9.5 Verification

The Contractor shall verify that the injected mass of geopolymer matches the design quantities.

The Contractor shall agree the scope of any long-term monitoring if required by the Project Specification.

The Contractor shall propose with the Tender how they intend to demonstrate that the performance criteria specified in the Project Specification have been met.

GUIDANCE

Long-term monitoring of building structure performance may be required to demonstrate effectiveness of the treatment programme, but this is generally a matter for the building owner or insurer and professional advisors.

Acceptable limits of the post treatment movements are building and structure specific, and should be agreed on a case by case basis with the Engineer.

10 Controlling real-time displacement

All materials and work shall be in accordance with Clauses 1 to 4 of this specification.

10.1 Introduction

This clause provides requirements for using expanding geopolymers to control displacements in real-time.

Certain construction activities, such as tunnelling or excavation, may cause ground movements which can have a detrimental effect on the ground surface and the surrounding built environment.

Compensation grouting (see e.g. Kettle, 2017) can be used to minimise surface and subsurface ground settlements, by providing a carefully controlled and monitored real-time compensation to these movements. Expanding geopolymers can be used as an alternative to conventional grout systems.

10.2 Project Specification

The following matters, where appropriate, shall be described in the Project Specification:

A. The cause, lateral extent and rate of development of the expected ground movement.

B. The required depth and spread of treatment, considering the cause of the ground movement to be compensated for and the potential for further-field impact (e.g. for tunnelling-induced settlements).

C. Specific ground investigation results.

D. Limits on ground and/or structure movements that are either permitted or required to be induced during the works.

E. The need for further treatment, if required.

F. Treatment verification methodology, and responsibility for monitoring movements, and setting trigger values.

G. Any other technical requirements.

GUIDANCE

For item C, as a minimum this would include Particle Size Distribution and SPT value (or equivalent)

10.3 Design of geopolymer injection

The Contractor's design shall define the process and area to be treated by real-time displacement control by setting the following parameters:

- The depth(s) of injection and the need for reinjection at specific locations
- The width and length of the treatment zone
- The spacing of injection points, typically 0.5-3.0m
- The direction of the injection tubes (vertical or inclined)
- The sequence of injection and durations between injections (e.g. injection periods of 15 seconds alternated with pauses of 1-2 seconds)
- The geopolymer to be used, considering the reaction time and distance between injection points
- The method of injection or reinjection, either:
    - Using multiple injection tubes at each injection point, or
    - Tube à manchettes (TAM) system

Each injection point shall have a unique identification code, so as to be easily integrated into the overall real-time displacement control system.

The application specific material properties for expanding geopolymer are listed in Clause 4.3. If the Contractor proposes values for properties that are outside of the ranges stated, then they shall provide justification in the GDR.

10.4 Execution

During treatment, pre-defined points shall be injected with geopolymer to counter displacements being caused concurrently by construction activities.

As the injection points are injected sequentially, it is important to understand the potential effect on the ground movements and any nearby structures. Trigger limits shall be set to ensure that any intermediate point during injection does not cause unacceptable effects on any assets to be protected. Actions to be taken upon reaching these trigger limits shall also be set. The responsibility for monitoring, the setting of triggers, and associated actions shall be as defined in the Project Specification (Item 10.2 F).

GUIDANCE

Two different approaches can be followed:

- Treatment of the entire thickness of compressible soil layers
- Partial treatment of the compressible soil thickness

10.5 Verification

A monitoring regime shall be designed and put in place to measure the impact on the ground surface or any surface or buried structures or assets which may be affected by the combined effect of the disturbance and ground treatment. The monitoring shall track one or more of the following, and shall be able to display the results in real-time (Burland et al., 2012) so as to allow the operator to respond in a timely manner to the measured changes:

- Displacements
- Strains
- Stresses

The responsibility for design and use of the monitoring system shall be as set out in the Project specification (item 10.2 F)

GUIDANCE

Examples of monitoring systems which may be used:

- Manual or automatic total stations measuring displacements of ground surface mounted prisms
- Precise manual levelling
- Fibre optic cables within boreholes to measure subsurface strains
- Inclinometers or extensometers within boreholes to measure subsurface displacements and strains
- Using a rotating laser

In addition to compliance with trigger levels, it is important that the data are presented in a graphical format. In its simplest form, this may be produced by hand, but ideally proprietary monitoring software should be used to automatically produce contours of movement.

11 Controlling liquefaction

All materials and work shall be in accordance with Clauses 1 to 4 of this specification.

11.1 Introduction

This clause provides requirements for using expanding geopolymer as a solution for mitigating the risk of liquefaction in coarse grained soils.

The induced compaction effect from the expansion of the injected geopolymer can reduce the liquefaction hazard for shallow ground formations by reducing the possibility for the ground to experience significant volume changes during seismic events. This specification chapter has been written under the principle that risk for liquefaction is too high and requires remediation to mitigate.

GUIDANCE

This solution can be cost effective compared to other remediation methods in situations where there are other constraints such as buildings.

This chapter is for use in procuring expanding geopolymer works, not for a whole assessment of liquefaction and so has been written under the assumption that this has already been carried out. The performance of the grouting trials is useful to validate the selection of the type of geopolymer, as well as for the definition of the borehole spacing, and geopolymer injection pressure and volume. All these aspects allow the designers to adopt an observational method for a design optimization. Laboratory tests might also be considered as trials when the possibility of collecting undisturbed samples is considered appropriate.

The Engineer should specify a method for verification which is consistent with the analysis and considers the known site constraints.

11.2 Project Specification

The following matters, where appropriate, shall be described in the Project Specification:

A. Existing assessment of soil liquefaction risk and liquefaction factor of safety.

B. The geological and geometrical model obtained from the site investigation, where the depth and lateral extension of the area to be treated is identified.

C. Treatment verification methodology and required soil properties (including required criteria to be met).

D. The requirements for pre and post-treatment ground investigation to baseline and verify soil properties.

E. The details of field grouting trials to validate the theoretical design and injection methodology, if required in Clause 2.1 Item C.

F. Any other technical requirements.

GUIDANCE

For item A, BS EN 1998-5:2004 provides guidance on appropriate FOS to reduce the risk to an acceptable limit. This assessment is likely to be outside of the capability of a specialist geopolymer contractor, and this item assumes that the assessment has been carried out ahead of production of the specification.

The following information would be expected to be obtained to inform a liquefaction susceptibility assessment:

- Ground profile
- Groundwater pressures (in-situ measurements)
- Index properties of soil layers including grading (fine and coarse), plasticity, moisture content
- Soil relative density or indicator thereof
- Soil shear wave velocity

The following information should usually be provided for the liquefaction assessment:

- Peak Ground Acceleration (PGA)
- Earthquake magnitude (Mw)

For item C, it is important that verification criteria established as part of the Liquefaction Hazard Assessment are communicated to the specialist contractor prior to them carrying out the design. These will form the basis of verification.

For item D, the Engineer should specify a method for verification which is consistent with the analysis and considers the known site constraints.

For item E, the performance of the grouting trials is useful to validate the selection of the type of geopolymer, as well as for the definition of the borehole spacing, and geopolymer injection pressure and volume. Specifying a trial can allow the designer to adopt a method based on the trial observations for a design optimization. Laboratory tests might also be considered as trials when the possibility of collecting undisturbed samples is considered appropriate.

11.3 Design of geopolymer injection

The Contractor shall consider the existing assessment of soil liquefaction risk, and the geological and geometrical model provided by the Engineer to develop the injection scheme.

The Contractor shall use an appropriate constitutive model in the design of the geopolymer injection scheme. The details of the model used and appropriate validation shall be included in the GDR (Clause 2.3).

The application specific material properties for expanding geopolymer are listed in Clause 4.3. If the Contractor proposes values for properties that are outside of the ranges stated, then they shall provide justification in the GDR.

GUIDANCE

This is a complex area, and the contractor should be required by the specifier to demonstrate suitable capability to design these mitigations.

The choice of the constitutive law for the ground is a key aspect for the prediction of the ground response due to the treatment. The expansion of the geopolymer tends to induce large deformation in the ground, in particular where a low relative density characterizes the initial state of the material. With this in mind, solutions based on simple elastic models should not be considered to provide reliable results. The response of the ground is better reproduced considering models based on elasto-plastic constitutive laws. The compaction effect caused by the expansion of the geopolymer will decrease with the distance from the injection point. It is therefore possible to consider the presence of a region around the injection point that deforms more compared to regions at further distances. This region is usually identified as a plastic zone, where plastic deformations govern the response of the ground.

In the case of coarse-grained materials, a good compromise for the improvement design is the adoption of an elastic-perfectly plastic model using the Mohr-Coulomb criterion. Cavity expansion theory allows the determination of the equilibrium pressure between the geopolymer and the ground, which is achieved at the end of the expansion process of the geopolymer, along with the final volume of the expanded geopolymer in the ground. This calculation can be performed considering either a small strain or large strain approach. In the first case an analytical closed form solution was obtained by Carter et al. (1986); in the second case, an analytical solution can be found in Yu and Houlsby (1991). Then, given the equilibrium pressure, the stress state and the deformations in the ground can also be calculated.

The injection material for the treatment to reduce soil liquefaction is generally the same as the geopolymers used in ground improvement applications. Geopolymer final mechanical properties are directly dependent on the surrounding ground conditions and structural loads. The strength of the cured geopolymer material is strongly dependent on the initial volumetric weight applied.

The rheological behaviour of the geopolymer is described by the swelling curve (Manassero et al. 2016) that relates the volumetric expansion of the resin with its swelling pressure; the determination of the swelling curve can be performed with special laboratory tests adopting an ad-hoc oedometer testing apparatus (Buzzi et al. 2010, Manassero et al. 2016).

The density and viscosity of the geopolymer are also required in order to evaluate the size of the bulb of the ground that is permeated by the geopolymer during the initial injection. Along with this information, the injection pressure and volume of the geopolymer are also key aspects for the assessment of the initial bulb volume.

The main difference of using expanding geopolymer with respect to classical grout materials (such as cement) is that the injection pressure is only required for the initial permeation of the geopolymer in the ground and the formation of an initial bulb of resin; the expansion of the bulb, which is determined by the chemical reactions between the two components of the geopolymer, is responsible for the compaction of the ground.

The final volume of the expanded bulb is obtained from the intersection of the geopolymer rheological curve and the cavity-expansion curve of the ground, which corresponds to the equilibrium value between the swelling pressure of the geopolymer and the confining pressure of the ground.

Due to the high hydraulic conductivity of coarse-grained materials, the treatment process is usually considered a drained process and the analysis is carried out using an effective stress approach.

The definition of these design parameters depends on a series of factors, such as the soil type and properties, the type of geopolymer, the depth of the treatment (that is related to the stress state), and the desired improvement range. Generally, the spacing among the injection points is lower for ground treatments executed at more shallow depth (Burland et al. 2012); this aspect is mainly due to the lower expected relative density and confining stress with respect to deeper ground layers, and the possible upheaval of the ground surface that may reduce the compaction effect of the improvement.

The grid geometry and spacing of the injection points can be evaluated using a simplified approach proposed by Mitchell (1981). The methodology was developed for classical compaction grouting techniques and it is based on two main assumptions:

- the absence of vertical displacement in the ground during the compaction process, and

- The volume of injected material is equal to the variation of the void volume in the ground.

With respect to the second assumption, it is important to highlight that, in the case of an expanding geopolymer, the final expanded volume of the geopolymer has to be considered and not the initial injected volume.

Further guidance can be found in BS EN 12715 (2000).

11.4 Execution

The Contractor shall consider the liquefaction analysis and the potential impact of the site works when planning the execution. For liquefaction remediation, explicit consideration on the effect of treatment on pore pressures shall be considered in the design and clearly communicated to site personnel.

The Contractor shall carry out a pre-treatment ground investigation to establish a baseline for demonstrating the effectiveness of the geopolymer works. If the methodology for establishing the effectiveness is not specified in 11.2 Item C then the Contractor shall propose a method for acceptance. The Contractor shall propose the testing layout and scope for acceptance by the Engineer.

The Contractor shall review the results of the pre-treatment ground investigation against the information provided by the Engineer. If the results of the two investigations are not consistent then the Contractor shall inform the Engineer of the discrepancy. The Contractor shall seek instruction from the Engineer on the validity of the original liquefaction analysis considering the pre-treatment ground investigation, and confirmation as to how to proceed.

GUIDANCE

BS EN 12715 (2000) provides general guidelines for grouting works and it defines the following four phases:

1. drilling,
2. grout preparation,
3. grout placement, and
4. grout sequences.

When the treatment is mitigating the liquefaction hazard, the monitoring of the work does not require additional factors with respect to what is usually considered for general geopolymer works.

Typical monitoring factors are the control of the type geopolymer to be used for the treatment, the drilling activities, the injection activities, the surface displacement, and the possible environmental impact of the treatment.

11.5 Verification

The Contractor shall carry out post-treatment ground investigation with testing locations as close as practicable to the pre-treatment locations within the treated volume of ground. The investigation shall include tests carried out using the same method and by the same Contractor to ensure a comparison can be made between the two set of results. The Contractor shall propose the testing layout and scope to the Engineer for acceptance.

Unless otherwise specified in the Project Specification, a representative number of investigation points, not less than 4 in number, taken across the areal extent of treatment and to at least 2m beyond the base of the soil layer requiring improvement shall be formed. Points shall be positioned over and between injection locations.

Unless otherwise specified in the Project Specification, CPT end resistance and/ or suitably corrected SPT N values shall be used to determine the cyclic shear resistance (CSR) of the untreated and treated ground at a representative range of effective vertical overburden stresses in accordance with BS EN 1998 Part 1. The CSR shall be compared to the cyclic shear stress ratio (CSS) for the soil to determine the need for improvement and whether sufficient improvement has been provided by the treatment.

The Contractor shall submit their proposed verification layout and methodology with the tender.

The Contractor shall determine the post-treatment soil properties to verify against the requirements of Clause 12.2 Item C.

If the specified post-treatment soil properties are not achieved, the Contractor shall plan additional works to ensure this is corrected. The proposed works shall be submitted to the Engineer for acceptance.

Once additional works have been carried out, the Contractor shall re-verify the works using appropriate post-treatment ground investigation as described above.

GUIDANCE

Where the aim of the treatment is to improve the seismic response of the ground (CSR) then the preferred method of ground investigation is to use electric cone penetration tests with measurement of dynamic and static pore water pressure (SCPTu). These tests give a continuous record of measurement. A seismic cone is used to measure the soil shear wave velocity.

A less suitable but potentially viable alternative to provide an indicator of soil relative density is to use close centre standard penetration tests in boreholes. An alternative means of shear wave velocity measurement shall also then be used, for example multi-spectral analysis of surface waves (MASW), downhole seismic profiling or cross hole seismic profiling.

Where the aim of the work is to reduce vibration transmission from external sources to prevent liquefaction then it may be appropriate to measure Peak Particle Velocity (PPV) at source and receptor both pre- and post-treatment.

12 Geopolymer Columns

All materials and work shall be in accordance with Clauses 1 to 4 of this specification.

12.1 Introduction

This clause provides requirements for supporting structures by expanding geopolymer columns to: increase a structure's ability to bear load, such as increasing its foundation resistance; enhance settlement characteristics, by improving foundation ground stiffness; or reinforce the existing structure against increased loads.

These applications are fundamentally very similar; however, the differences lie in how the method is verified.

In each application the process is carried out by injecting geopolymer into geotextile elements with or without a reinforcement steel core. The bearing capacity of the geopolymer column is generated either by:

- Structural compression strength of the injected geopolymer density
- Geotechnical bearing capacity of the injected geotextile column sheet
- Load bearing capacity of the steel reinforcement core pile
- Increased ground stiffness by the expansion of geopolymer

The process allows geopolymer material localisation control by geotextile columns in loose and weak soils where traditional geopolymer grouting may be ineffective.

The method can be applied through existing structures without additional load transfer structures. In addition to load bearing application the process can be used for improving lateral or tension force, such as anchoring.

12.2 Project Specification

The following matters, where appropriate, shall be described in the Project Specification:

A. Nature of the structure to be supported, incl. reinforcements.

B. Purpose of the treatment

C. Nature of site to be treated (under foundations or not under foundations)

D. Soil type and stiffness

E. The target bearing/tension values

F. Treatment zone, if applicable

G. Treatment verification methodology

H. Other technical requirements

GUIDANCE

For item A, this could be end bearing, geotechnical bearing with friction or cohesion, anchoring, local compaction, part of other ground improvement etc.

For item G, this could be Pile load/tension testing, DPTs or CPTs for soil strength, pressuremeter, geotechnical or geopolymer design calculations

12.3 Design of geopolymer injection

The Contractor's design shall consider:

- Purpose of the treatment (for example: load bearing, tension, compaction)
- The design of the system to achieve the specified parameters or performance, including consideration of spacing, levels, volumes of injections, use of steel reinforcement, choice of material
- Structural assessment of the foundation
- Connection with the existing structure
- The impact of the treatment on existing structures
- Possible hybrid injection as part of the treatment (grouting partly without geotextile sheet)
- The requirement for any additional future loading
- The requirement for any future interventions (where, for example, the proposed geopolymer treatment will not treat the underlying cause of the settlement but simply maintains the asset within operational tolerances)
- Proposed method of verification

The application specific material properties for expanding geopolymer are listed in Clause 4.3. If the Contractor proposes values for properties that are outside of the ranges stated, then they shall provide justification in the GDR.

GUIDANCE

The contractor should normally carry out prior to the geopolymer column treatment, a structural assessment to verify the loadings of the structure and its bearing stress through the foundation. Together with ground investigations they should provide, were appropriate the following details in particular:

- Stratification or layering and engineering properties of each layer of ground
- Soil index and classification properties, including close centre moisture contents, Atterberg limits, shrinkage limits, coarse and fine particle size distribution
- Ground water levels
- Configuration of the foundation system
- Penetration resistance by dynamic cone penetration test (DPL/DPM) or CPT or SPT
- Level surveys of the structure and/or load-settlement performance tests, for example plate bearing tests.
- Depth of the sufficient bearing ground or bedrock level.

Based on the collected structural and geotechnical information, the contractor shall determine the area and depth of the treatment and required performance criteria and/or characteristic of the geopolymer columns, including at least one of the following:

- Expansion and/or soil compaction
- End bearing
- Geotechnical bearing (friction/cohesion)

The positioning and locations of geopolymer columns shall be specified by taking into account limiting underground structures and to be considered with structural stability assessment where required.

12.4 Execution

Real-time monitoring of material flow rate and quantity shall be carried out throughout the geopolymer injection in conjunction with position monitoring of the supported structure to ensure that the column geotextile column or movement of the structure does not exceed the specified limits or constraints in the design.

In the absence of provided limits, the Contractor shall cease work when movement of the structure/ground is detected and shall seek guidance from the Engineer.

12.5 Verification

The method of verification shall be identified by the Contractor in the design.

The targeted properties of the injected geopolymer columns shall be verified by injection records or post-testing.

The Contractor shall make and produce appropriate records for each geopolymer column injection independently to verify the designed quantity has successfully been injected.

Where required, the Contractor shall carry out geopolymer injection until the point at which post-treatment verification measurements demonstrate the target levels have been achieved.

If the target levels are not achieved once all planned injections are carried out, the Contractor shall plan additional works to achieve the targets. The proposed works shall be submitted to the Engineer for acceptance.

GUIDANCE

Using geopolymer columns for load bearing the design verification shall be carried out according to Eurocode 7. The design shall be based on one of the following approaches:

- Static load tests – which have been demonstrated to be consistent with other relevant experience
- Empirical or analytical calculation – whose validity has been demonstrated by static tests in comparable situations (validation would concentrate on comparison of ground properties, and verifying the design parameters)
- Dynamic tests - whose validity has been demonstrated by static tests in comparable situations
- Observed performance of a comparable foundation – provided this approach is supported by the results of site investigations and ground testing (validation would concentrate on comparison of ground properties and verifying the design parameters).

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