Use of expanding polyurethane resin to remediate expansive soil foundations

Olivier Buzzi, Stephen Fityus, and Scott W. Sloan

Abstract: Injection of expansive polyurethane resin can be used to remediate differential settlement issues. The resin is injected incrementally under a structure to achieve a desired foundation level, forming a composite resin–clay material. This solution is not well documented in the literature and some questions arise on the long-term performance of this solution. As injection is usually carried out in a settled soil mass that is dry and dessicated, rehydration of the soil after injection may lead to swelling of the leveled foundation and overlifting of the structure. Experimental research undertaken to investigate this rehydration issue and determine if there is a risk of overlifting in the long term is presented here. In situ and laboratory testing was performed to investigate the most fundamental aspects of the problems. This included the in situ injection of resin, study of resin propagation in the soil mass, influence of resin on the hydraulic conductivity of the soil mass, and large-scale swelling tests. The results suggest that, even though the resin cannot prevent the rehydration of the soil mass, the risk of overlifting in the long term is limited.

Key words: expansive soils, differential settlement, polyurethane, shrinkage, swelling.

Résumé : L'injection de résine expansive de polyuréthane peut être utilisée pour remédier à des situations de tassements différentiels. La résine est injectée graduellement sous la structure afin de positionner la fondation au niveau désiré, et ce en formant un matériau composite argile–résine. Cette approche est peu documentée et plusieurs questions sont soulevées quant à la performance à long terme de cette approche. Puisque l'injection de résine est normalement effectuée dans un sol consolidé et sec, la réhydratation du sol après l'injection peut entraîner un gonflement de la fondation et un soulèvement de la structure. Cet article présente des travaux expérimentaux entrepris dans le but d'évaluer la réhydratation et de déterminer les risques de soulèvement à long terme. Des essais in situ et en laboratoire ont servi à investiguer les aspects les plus fondamentaux du problème. Ces aspects incluent l'injection in situ de la résine, l'étude de la propagation de la résine dans le sol, ainsi que des essais de gonflement à grande échelle. Les résultats suggèrent que même si la résine ne peut pas prévenir la réhydratation du sol, le risque de soulèvement est limité.

Mots-clés : sols expansifs, tassement différentiel, polyuréthane, rétrécissement, gonflement.

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Introduction

Expansive soils are responsible for causing distress to lightly loaded structures. The effect of significant swelling pressures on lightweight, low stiffness structures can lead to significant tilts, deflections, and bending, with consequent unacceptable levels of distress in relatively weak structures (Wray 1995). There are few effective and economical approaches that can fix the problem and prevent it from reoccurring, and solutions such as underpinning are greatly disruptive and involve costs that may approach the replacement cost of the structure (Freeman et al. 1994).

Underpinning involves attaching additional structural elements to a foundation, usually to improve its stiffness and stability. As full underpinning of an existing, operational structure is usually impractical (and often considered unnecessary), it is common for underpinning works to be carried out locally on areas of the foundation that are considered to be most affected by foundation problems and areas that can be more easily accessed. As differential settlements are caused by localized variations in foundation characteristics, localized application of underpinning works has the potential to change the relative foundation performance in different areas beneath the structure, without improving the overall foundation performance (Walsh and Cameron 1997). Any localized treatment of a foundation to correct a perceived inadequacy must be designed on the basis of a comprehensive and correct interpretation of all factors that have caused the problem, otherwise the problem can be exacerbated.

A particular class of foundation problem arises in situations where a lightly loaded shallow foundation is constructed on an expansive soil with nonuniform initial moisture conditions (e.g., a tree removed before construction) or if the initial moisture equilibrium is changed, for example by planting a tree (Snethen 2001). The action of building a slab in itself affects the moisture exchange and moisture equilibrium (Holland and Lawrance 1980). Another cause of problems is the natural spatial variability of soil expansiveness and (or) depth. In such situations, differential foundation movements may occur as the foundation soils

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come to moisture and stress equilibrium beneath the new structure.

Injection of expanding polyurethane resin is a common alternative to underpinning for individual houses, buildings, and paving slabs (see case history in Favaretti et al. 2004) for a wide variety of differential settlement situations. The pressure exerted by evolved gas during the chemical reaction that forms the resin lifts the structure. This solution does not require excavation or the installation of additional foundation structural elements, because the resin can be injected directly under the building by means of small diameter aluminium tubes. Where differential settlements are the result of consolidation or settlement–collapse of fill, resin injection is a reliable remediation option with predictable outcomes. However, when injected in expansive soils, which are often settled because of water-loss-induced shrinkage, a question arises regarding the long-term performance of the solution. Indeed, one may postulate that the re-leveled, injected expansive soil could swell excessively if it becomes re-wetted, thus locally overlifting the already leveled dwelling.

Polyurethane resins have been employed in geomechanics as a sealant to reduce seepage (Pro 2005) and other kinds of nonexpanding resins (e.g., epoxy or acrylic) have more commonly been employed in grouting (Shaw 1982). The use of expanding polyurethane as a filling and lifting agent in soils effectively makes it a geosynthetic, although its means of deployment are relatively unconventional when compared with premanufactured materials that are embedded in soils during earthworks. Very little data is available in the literature on the use of expanding polyurethanes as a soil treatment technique, particularly in expansive soils, or on the hydromechanical behaviour of the composite polyurethane resin–expansive soil material.

This study introduces injected expanding polyurethane as a geosynthetic material with a unique role to play in the engineering of expansive soils. It provides an overview of the potential long-term swelling issue associated with the injection of expanding polyurethane resin when used in expansive soils as a remediation treatment. Several fundamental aspects of the issue are considered, each one providing a piece of information for the overall understanding of the problem. This includes the process of in situ injection of resin, study of resin propagation in the soil mass, influence of resin on the hydraulic conductivity of the soil mass, and data on the swelling behaviour of injected and noninjected clay soils.

Expanding polyurethane resin

Polyurethanes are an extensive family of polymers that can be manufactured to achieve a wide range of physical characteristics in either expanded or nonexpanded states. Expanding polyurethane resins are formed from an exothermic reaction between a polyol and an isocyanate, mixed in specific volumetric proportions according to their particular product specifications. A large amount of carbon dioxide is produced during the reaction, causing volume expansion and producing a foam structure where gas bubbles (cells) are surrounded by rigid walls. The pressure exerted during expansion and the subsequent density of the resin depend on the extent to which the gas in the bubbles of the foam are able to expand before the resin hardens. The closed cell structure of the expanded resin is shown in Fig. 1.

The resin used in this research, which is a patented product of Uretek (Canteri 1998), reaches a volume up to 40 times greater than that of the initial components when expanding without confinement (free expansion). The resulting bulk density is around 37 kg/m^3. The expansion pressure developed and the final density depend on the confinement level. A pressure up to 10 MPa can be reached under highly confined conditions with corresponding densities up to 1000 kg/m^3 (Favaretti et al. 2004). The reaction time, which depends on the particular resin, is affected by the temperature of the components when mixed. For a foundation remediation application, an expanding resin that hardens within a few minutes is desirable, so that its effect on the foundation level can be evaluated soon after injection. Once injected, the resin is considered to be stable, as it is only sensitive to UV light and some synthetic chemicals that are not usually found in foundation soils.

The mechanical properties of the hardened resin depend on both its density and structure (Ford and Gibson 1998; Saha et al. 2005). Buzzi et al. (2008) determined that the microstructure is affected by the size and shape of the space into which the resin expands. Long, narrow spaces such as cracks cause the resin to rise preferentially along the crack producing an anisotropic cellular structure. Due to the rapid curing time, and the use of multiple small injections to control lifting, the resin structure is further affected when the resin that is injected later compresses the partially hardened resin that was injected earlier. When the resin forms veins in the ground, rising and transverse directions, i.e., primary and secondary directions of resin expansion, are clearly defined (Buzzi et al. 2008). However, the neat difference of mechanical response when compressing the homogeneous resin specimens along the rising direction or along the transverse direction (Tu et al. 2001) was not observed for the resin formed in the ground (Buzzi et al. 2008). Regardless of the direction of compression, hardening of the specimen was recorded once an axial strain of 5%–10% was exceeded. Then, densification took place at a very large strain (in excess of 50%) (as shown in Fig. 2).

Experimental program

A better understanding of the possible long-term swelling of the composite resin–clay foundation material requires several aspects of its behaviour to be understood:

(1) *How* does the resin propagate in the soil mass as it expands?
(2) *What* are the structure and properties of the soil–resin composite that is formed?
(3) *How* does the resin affect soil rehydration?
(4) *Does* the presence of resin increase the swelling potential of the soil through the filling of voids?

Experimental investigations were undertaken to clarify these specific points.

In devising an experimental approach to examine the potential overlifting issue, it was recognized that resin in the soil could have several possible effects: it could fill voids locally or it could fill all voids; it could partially or com-

Fig. 1. Scanning electron microscope image (100× magnification) of the free expanded polyurethane resin (density of 37 kg/m^3).

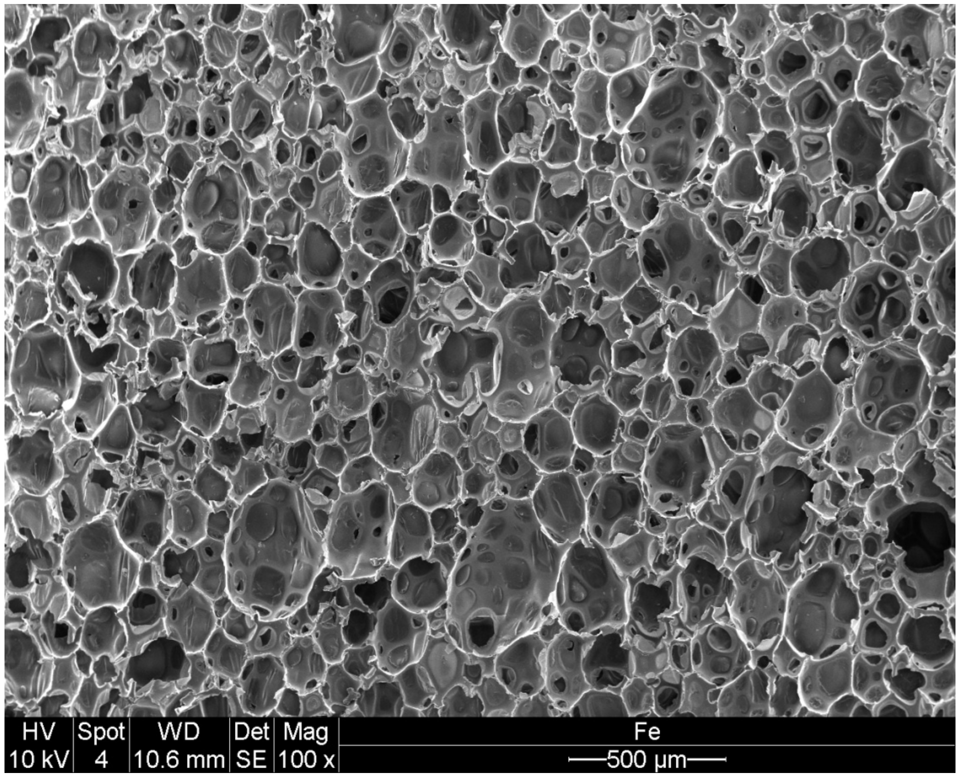
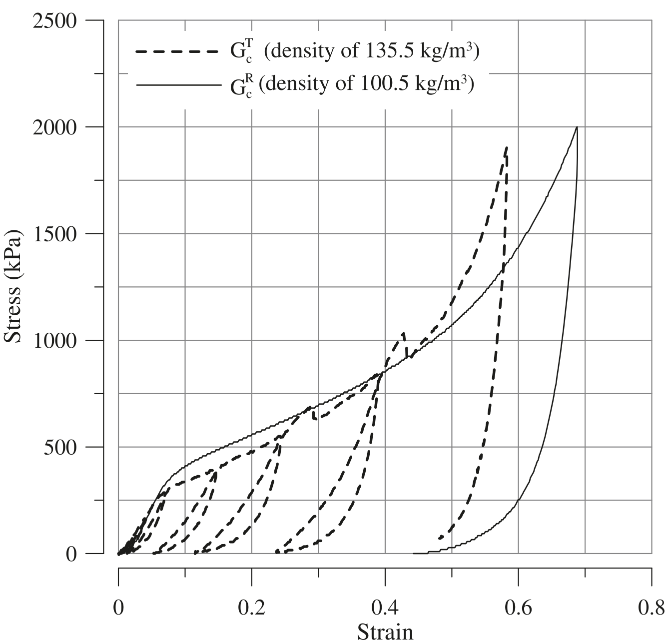


Fig. 2. Evolution of nominal stress versus nominal strain during an unconfined uniaxial compression test for the foam injected in situ. The dotted line corresponds to a compression in the transverse direction, Q_c^T, and the solid line to a compression in the rising direction, Q_c^R (after Buzzi et al. 2008).



pletely surround bodies of soil; it could act as a barrier to moisture, a moisture flow retardant or a moisture conductor. A key factor to consider is the role played by desiccation cracks. As "settled" areas of the expansive soil often occur because of localized drying-induced shrinkage, and as cracking is usually associated with shrinkage in expansive soils, it follows that areas to be treated with expanding resin are likely to be initially cracked. This makes it important to carry out both field and laboratory studies on soils that are naturally structured. The occurrence of cracking in Maryland clay is described well in Moe et al. (2003). An important consideration in experimental studies of cracked soils is to study a volume that is large enough to be reasonably representative of the cracked soil mass. The mean crack spacing of Maryland clay is around 60 mm, therefore specimen diameters of 300 mm or larger were considered sufficiently representative.

With these considerations in mind, the experimental approach adopted to assess swell potential in this study comprises

- A study of in situ injections of expanding polyurethane resin in a cracked, desiccated soil.
- In situ and laboratory permeability tests on injected and noninjected soils.
- Large-scale laboratory swelling tests on injected and noninjected soils.
- In situ monitoring of ground movements in injected and noninjected soils.

Each of these is described in the sections that follow.

Results

Study of in situ injections

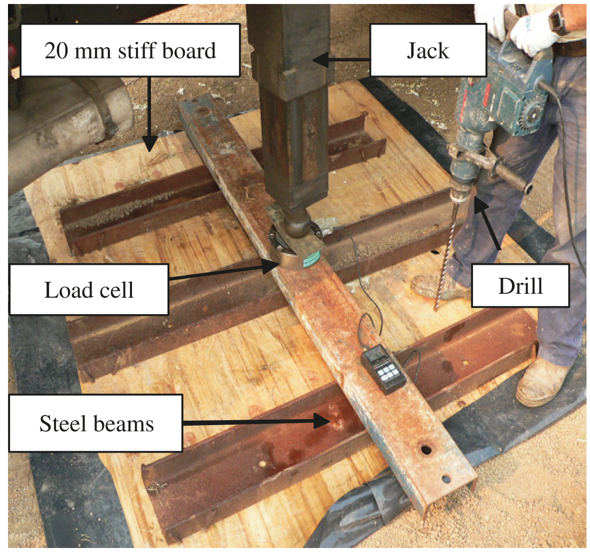
The results described in this section are derived from observations made from a series of resin injections that were performed in the field at the University of Newcastle's expansive soil test site located at Maryland, Australia (Fityus et al. 2004). Maryland clay has around 45% smectite, a liquid limit of around 75%, a plasticity index of around 50%, and a high swelling potential. Seasonally induced ground movements in open ground areas at Maryland vary from 45 to 75 mm. More details about the mineralogy, geological origin, and engineering properties of Maryland clay can be found in Fityus and Smith (2004). As the resin is usually injected at depth, under an existing structure, the injections for this study were carried out in soils subjected to a nominal surface load. A jack leg of a heavy truck acting on a loading frame made of steel beams was used to apply a vertical load of 40 kN to the 4 m^2 of stiff boards covering the injection zone, as shown in Fig. 3. The corresponding normal stress of 10 kPa is of the same order of magnitude as that applied by a typical house loading in Australia for a concrete slab on grade (Walsh and Cameron 1997).

It was not convenient to wait for the site soils to become dry and desiccated under natural conditions. Therefore, prior to injection, the top soil layer (30 cm thick) was removed to expose the clay to air drying for 2 months, so that the injected clay would be in a shrunken and desiccated condition. Four zones (each with four injection points per zone) were injected through holes drilled through the boards at the surface. The arrangement is shown in Fig. 4. The injection depths ranged from 0.5 to 0.75 m, to be either within or below the cracked zone. Although the depth of the cracked zone depends on the environmental conditions experienced by the soil mass and has been previously found to be as great as 1.2 m at Maryland (Fityus and Smith 2004), after the 2 months of drying, it was found to be around 0.7 m. (Note that all of the depths referred to here are relative to the excavated surface level.)

Around 80 kg of resin was pumped into the soil for each injection zone; that is, 20 kg for each of the four injection points. A lifting of 5–10 mm was measured at the center of the stiff board as a result of the injection process. The nature and extent of resin propagation was studied by extracting 300 mm diameter × 600 mm long pushtube samples and through observations made as the injected areas were progressively excavated.

Examples of observations after resin injection are presented in Fig. 5. From studying the results of injections in situ, it appears that the propagation of the resin in the soil mass is relatively unpredictable: although there is extensive invasion of resin in the cracks within around 0.5 m of the injection point (Fig. 5*a*), it certainly does not fill all of the cracks and it may travel more than one metre through wider, more persistent cracks. Indeed, it seems to follow the weakest path in the soil mass when expanding, which can be an existing crack or any other significant void in the soil mass. The propagating resin can enter cracks as small as 0.2 mm (Fig. 5*b*), but as a general rule, it propagates further in wider cracks and it is unlikely to travel more than a few centimetres in cracks less than 1 mm wide. A particularly important observation is that multiple injections of resin into cracks in soils leads to very anisotropic structures and textures, with features such as zones of different texture, compressed–distorted cells, and even large macrovoids. An example is shown in Fig. 5*b*, and a more detailed description of heterogeneous features is presented in Buzzi et al. (2008).

Fig. 3. Load application on the injection zone by means of a stiff board, a series of steel beams, and a jack. Photo shows injection holes in the stiff board being drilled, with four injection points drilled per injection zone.



On the basis of these observations, two propagation and lifting mechanisms were identified. These are illustrated in Fig. 6 and can be summarized as follows. If the injection takes place within the cracked zone (mechanism 1, Fig. 6*a*), then the resin is likely to intercept and propagate through existing cracks as it expands. In this case, it forms a smaller body near the point of injection (Fig. 5*a*) and it often reaches the surface, allowing it to act directly on the structure. It has been observed that, even if the resin propagates extensively through cracks to reach the surface, crack filling is still a very localized phenomenon and many of the cracks around the injection remain unfilled. Alternatively, if the resin is injected below the crack depth (mechanism 2, Fig. 6*b*), the resin tends to create a larger body at the point of injection and fills and propagates through relatively few cracks. It is unlikely to reach the surface; instead, it is able to lift the cracked overburden soil (Fig. 5*c*) and any overlying structure that may be present. This ability to lift at depth is due to the significant expansion potential of the resin, which can fracture the soil at the injection point if no major void is present. The significance of this point will be discussed further in the section titled "Evaluation of the results in the context of possible overlifting." As part of the resin propagation study, large injected and noninjected specimens were collected using a 300 mm diameter push–pull tube. These specimens were used to perform swelling tests in the laboratory.

Laboratory permeability tests

As a starting point to assess the effect of injected resin on the hydraulic conductivity of the treated soil mass, constant-head permeability tests were performed on specimens of clay and of resin formed in the laboratory (homogeneous) and in the field (heterogeneous) to compare their respective

Fig. 4. Schematic representation of the 4 m × 4 m injected area, divided into four injection zones (IZ1 to IZ4), with four injection points per zone as represented by the dots. Heave during injection was recorded close to the centre of each injection zone as shown by the crosses.

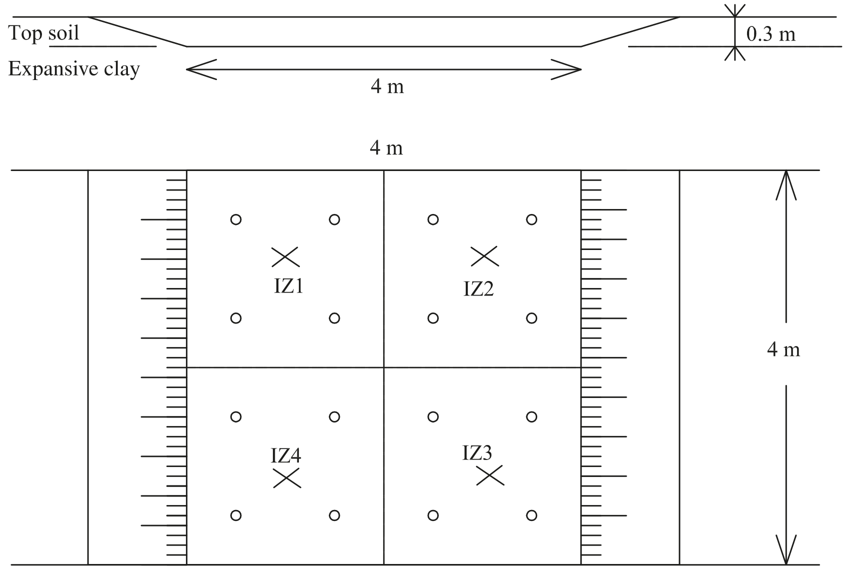


Fig. 5. Examples of observations after resin injection: (*a*) extensive filling of cracks of various size, (*b*) filling of fine cracks, and (*c*) surface crowning above section with deep (below crack) injection. White circles in (*a*) and (*c*) indicate injection tube locations.

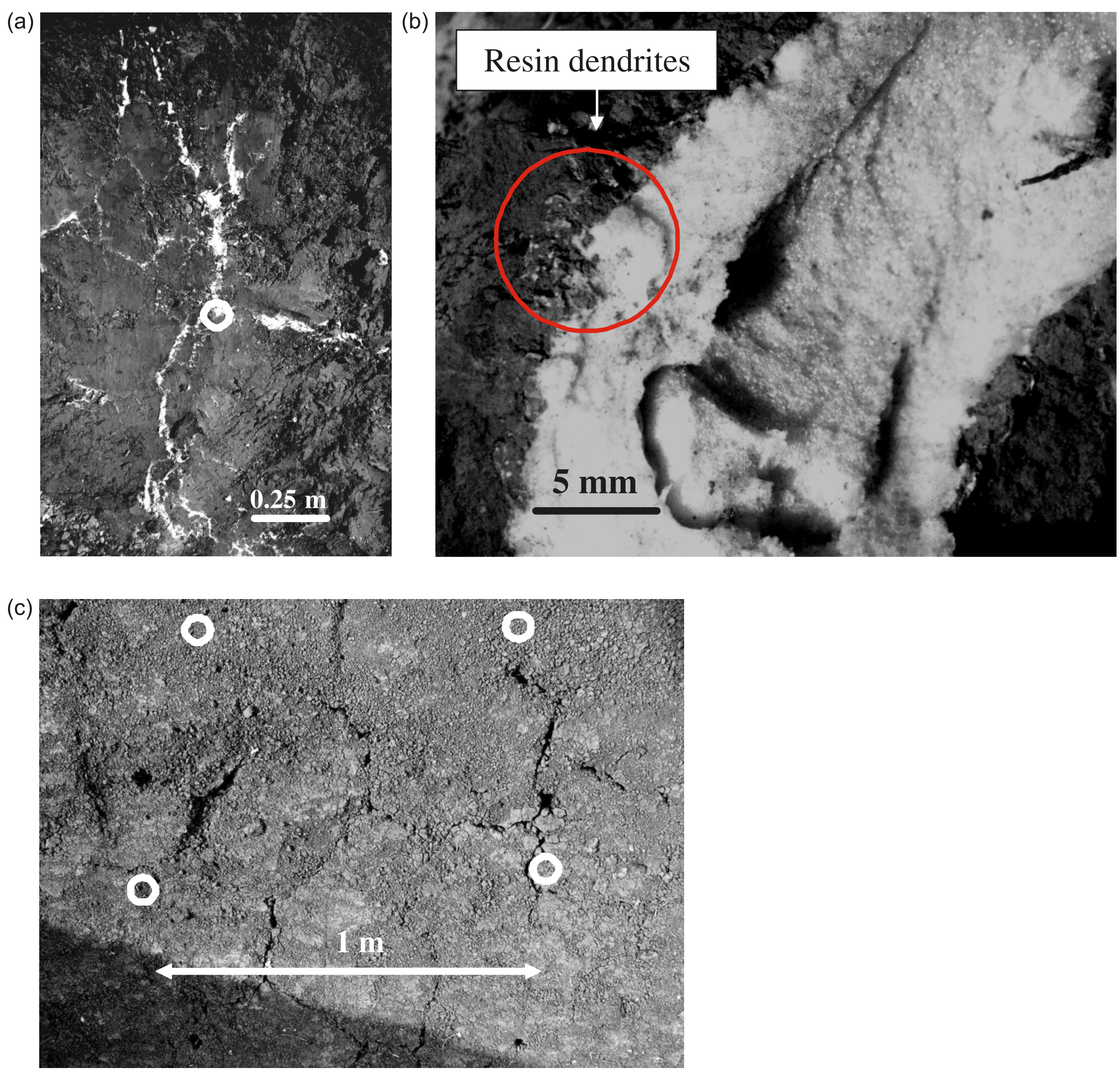
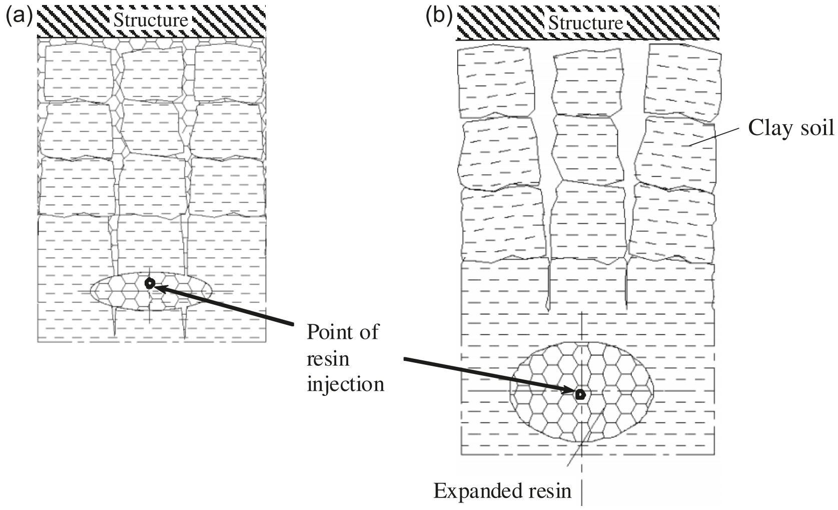


Fig. 6. Propagation of resin and lifting processes. (*a*) Mechanism 1: resin is injected within the cracked zone, it propagates within the cracks, reaches the surface, and lifts the structure. (*b*) Mechanism 2: resin is injected below the crack depth, it fractures the soil, creates a body, and lifts the cracked soil and the structure.



permeabilities and the influence of the structure on permeability (Buzzi et al. 2008).

Hydraulic conductivities were measured under a head difference of 25 kPa using a Rowe cell controlled by pressure–volume controllers. A conventional Rowe cell arrangement was used to test the homogeneous clay and resin specimens; however, the resin specimens formed in situ were mostly too thin to allow a suitable sample to be cut from the available material. Also, the specimens were too irregular to be confined in a standard Rowe cell and attempts to test free-standing thin veins of resin failed when the resin deflected in response to the applied head difference, causing the cell to leak. To overcome these problems, a modified version of the Rowe cell was designed to test the heterogeneous specimens. The modification is described in detail in Buzzi et al. (2008) and allows the resin to be confined by two layers of clays with no leakage at the interface between the ring and specimen.

The hydraul;ic conductivity of Maryland clay was measured to be around 10^{-10} m/s, of the order of magnitude expected for an intact clay. Eleven successful tests were conducted on specimens of resin with a range of different densities. A permeability ranging from 10^{-8} to 10^{-9} m/s was measured for the resin of lowest density, i.e., 37 kg/m^3. The measurable conductivity is attributed to local defects and (or) thinner (more fragile) cell walls in these materials. For higher values of density, it has been observed that the homogeneous resin is actually not permeable (water does not flow). Injection pressures up to 200 kPa have been applied without obtaining a flow, which can be explained by the smaller closed cell structure and thicker cell walls.

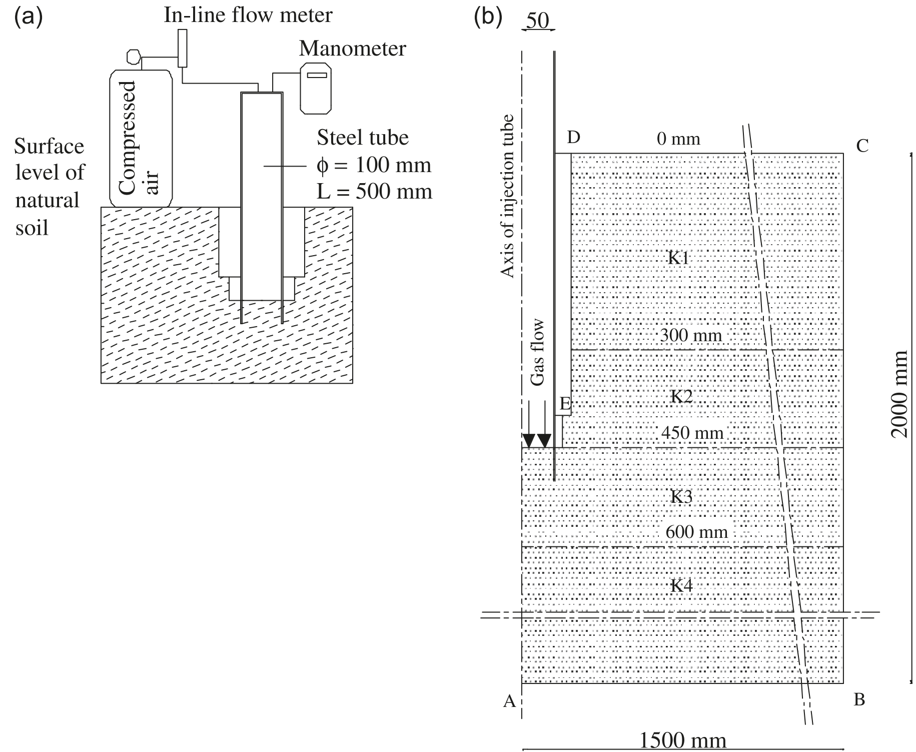
Only three tests could be performed on the resin formed in the ground due to the difficulty in obtaining and testing satisfactory specimens. Resins formed in situ, despite their relatively higher density, were actually found to be permeable (permeability of around 10^{-10} m/s). This is presumably due to defects in the microstructure that are inherent because of the incremental injection of resin into the ground (Buzzi et al. 2008). The permeability of such a material is lower than typical values of permeability of intact clays, which suggests that the veins of resin could be considered to act as hydraulic barriers provided that the resin veins actually form a continuous physical barrier.

In situ permeability tests

Laboratory tests on soils and resins are useful to understand their relative permeabilities, but the more relevant permeability to consider for a foundation soil is that of the structured composite (injected) soil mass. It has been shown that natural soils are made of interparticle voids and macropores including cracks and holes due to roots or worms (Jayawickrama and Lytton 1993). In dry expansive clay soils, cracks dominate the macropore population.

Expansive soil masses can actually be considered as dual permeability systems, with a crack porosity that is several orders of magnitude greater than that of the intact soil. When resin is injected into an expansive clay, it invades the macropores but cannot enter the micropores. As the macroporosity dominates the moisture exchange in a foundation soil, it is essential that the effect of the injected resin in reducing or even eliminating the macroporosity be understood. Permeability is usually estimated on the basis of measured flow characteristics of water when it is forced to permeate a porous medium in a controlled way. The permeability of a cracked clay soil is difficult to measure, as a large representative volume is needed and water cannot be used as a permeation medium as it changes the crack porosity it is trying to measure. Wells et al. (2006) developed a method of estimating the macropore hydraulic conductivity of a cracked expansive soil from the results of an air permeability test. This method was adopted here to determine the effect of resin injection on the permeability of cracked Maryland clay. To do this, air permeability tests were performed in two areas of Maryland clay under dry conditions: one area was treated with resin injection and the other was not.

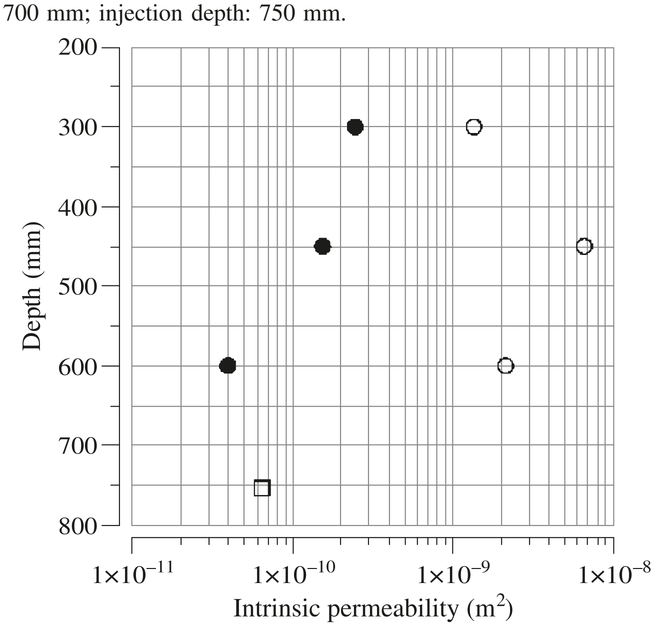
Fig. 7. Schematic representation of the airflow permeability approach to the measurement of hydraulic conductivity in cracked clay soils: (*a*) experimental setup; (*b*) finite element model used to back-calculate air permeability. ϕ, diameter; *L*, length.



The application of air permeability testing to estimate hydraulic conductivity is a multi-step process. In the first step, a series of tests is performed by embedding a thin-walled steel tube in the soil at the base of a borehole at depth intervals of 150 mm. At each depth, different flows of air are delivered to the soil and the pressures applied to achieve them are measured. The experimental arrangement is shown schematically in Fig. 7*a*. In the second stage, a finite element model is used to back-calculate the permeability to air of the soil mass, by trial and error, so that the determined permeabilities of the soil layers are those that predict the air pressure–flow relationships measured in the test. The geometry of the finite element model used is shown in Fig. 7*b*. In the third stage, the intrinsic permeability of the soil mass is calculated from the air permeability and then the hydraulic condictivity is calculated from the intrinsic permeability. A more detailed account of the process applied to this study is presented in Wells et al. (2006). The results of the air permeability tests are presented in Fig. 8, expressed as intrinsic permeabilities.

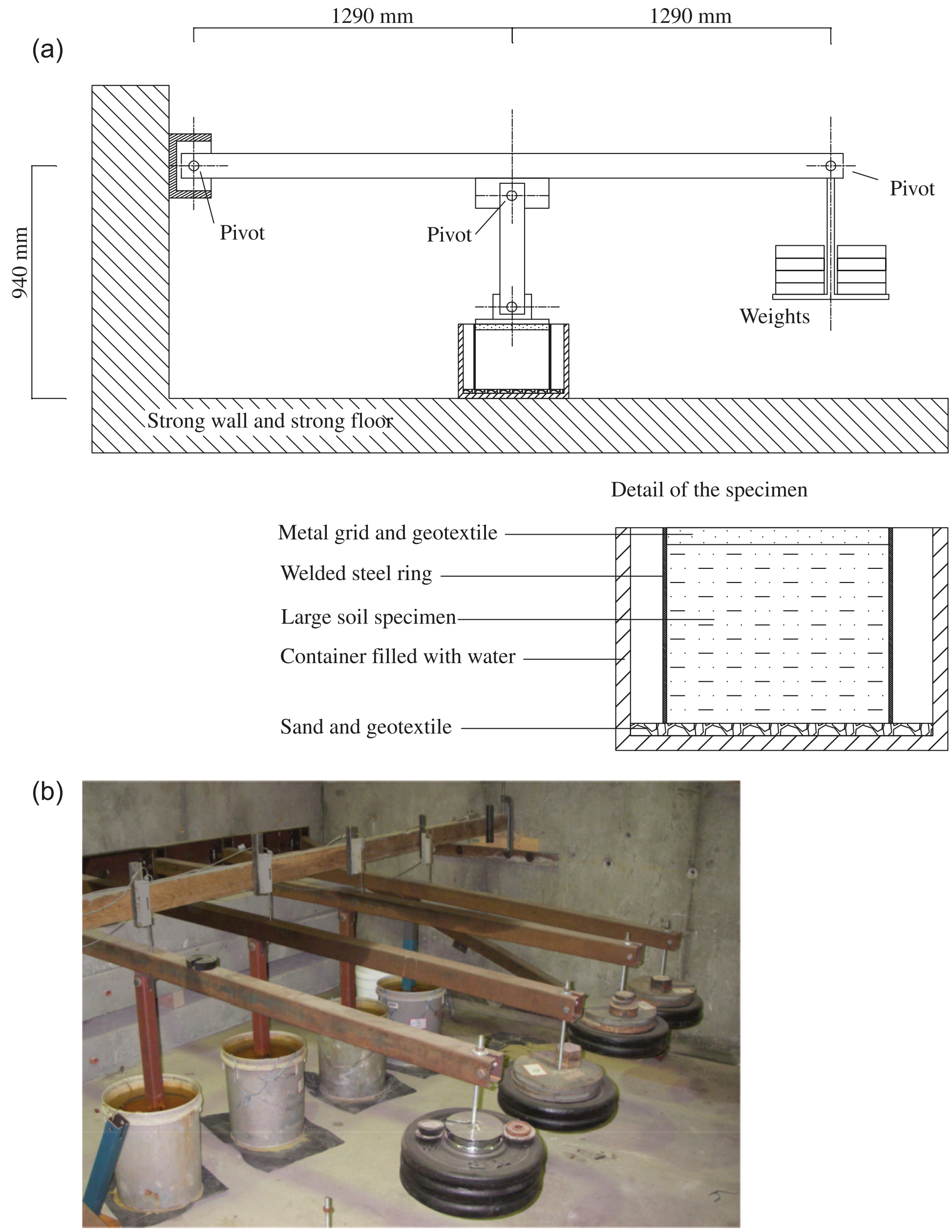
Noting that the depth of cracking was 700 mm at the time of testing, the results show that the permeability of the untreated cracked soil (open circles in Fig. 8) is 30–100 times greater than the intrinsic permeability of the uncracked soil (square in Fig. 8). The results also prove that the injection can locally decrease the permeability by a factor up to 50. Differences of at most a factor 2 were observed by testing the permeability of the noninjected soil at different locations. However, this reduction is likely to be very localized around the injection point and is highly dependent on the amount of resin injected and on its propagation.

Fig. 8. Profiles of intrinsic permeability determined from air permeability tests. Open circles are from tests in untreated soil, solid dots are from tests in resin-injected soils, and the square is the intrinsic permeability of the uncracked soil. Depth of cracking: 700 mm; injection depth: 750 mm.



The values of permeability in Fig. 8 can satisfactorily be used as an element of comparison to discuss the effect of the resin or the cracks on the permeability of the soil mass. However, conclusions about absolute values of permeability

Fig. 9. (*a*) Schematic of the large swelling test apparatus. (*b*) Photograph of the apparatus. The specimens (300 mm in diameter and 250 mm high) were tested under 25 kPa of vertical stress.



cannot reasonably be drawn, as discussed in Wells et al. (2006), due to the cohesive nature of the soil.

Laboratory swelling tests

To explore the effect of resin on swelling behaviour directly, a series of swelling tests under constant stress (25 kPa) were conducted on specimens of both injected and noninjected soil (two injected and two noninjected) using a large-scale oedometer arrangement. The samples were allowed to swell for up to 6 months.

Because of the scale of cracking in Maryland clay, to ensure that the results were truly representative, the tests were carried out on large specimens with a diameter of 300 mm and height of 250 mm. All of the specimens were obtained from the Maryland field site using 300 mm diameter push-tubes. They were all sampled on the same day after injection so that they contained a comparable density of cracks, but with a variable amount of resin. Despite the fact that the injections were performed in a dry soil, the specimens were not optimally dry when sampled from the field (in situ water content of around 32% on the sampling day), due to experimental and weather constraints. They were then exposed to air drying in the laboratory for 8 months to reach a water content estimated at 7%. During the drying process, the clay shrank further and some cracks opened. The dry density of the specimens before testing was around 18 kN/m^3 (±0.5 kN/m^3).

During the tests, the samples were tested under lateral confinement provided by welded steel rings. No special arrangement was taken to limit friction on the side of the rings, which is not detrimental to a comparative study. Geofabric and fine metal grids (porous plates) were placed at the top and bottom of the specimens to provide containment and to allow hydration. The experimental setup is shown in Fig. 9.

The results of the large swelling tests are shown in Fig. 10. It can be seen that generally the response of the noninjected specimens (2, 4) is fairly consistent. In contrast, the swelling behaviour of the injected specimens varies significantly in both magnitude and rate. This can certainly be attributed to the structure and amount of resin in each specimen. In particular, specimen 3 contained around 4% of resin formed in vertical veins, from the bottom to the top of the specimen. Two major veins and several minor veins can be seen in Fig. 11. Specimen 1 contained around 6% of resin but no vertical veins, and the resin mainly formed a subhorizontal layer at the top of the specimen, a part of which can be seen in Fig. 11.

The injected specimens consistently swelled much less than the noninjected specimens. It is suggested that the resin does not only fill some cracks when it expands but also opens many of them, as a sort of soil fracturing illustrated in Fig. 6*a*. As a consequence, more open cracks can be found in the injected specimens tested and the vertical swelling is reduced.

The difference in swelling magnitude between injected specimens 1 and 3 can be explained by the restraining action from the vertical veins of resin. The subhorizontal resin layer (specimen 1) can only delay hydration but does not mechanically prevent swelling; whereas vertical veins (specimen 3) tend to create a nonswelling skeleton, thus limiting the amount of swelling.

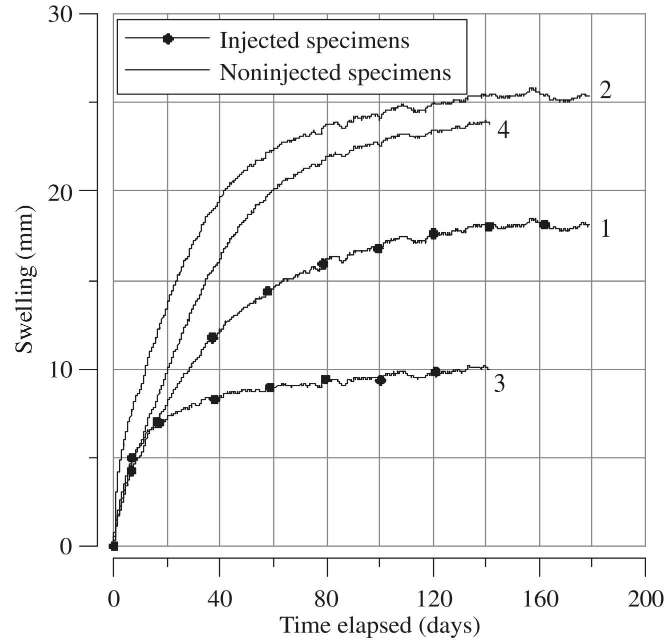
In situ monitoring of swelling

An alternative way to directly evaluate the swelling potential of injected soils was through the in situ monitoring of a resin-injected patch of soil at the Maryland field site. The patch of 3 m × 3 m was injected at a depth of 1.5 m during dry conditions in March 2006, whilst being subjected to a 10 kPa surface loading. The resin was delivered through 12 injection points, at a rate of around 20 kg per injection.

The movement of the ground surface of the injected patch was monitored for 3 years (Fig. 12). To give the results a basis for comparison, ground surface levels in two adjacent areas without resin injection were also recorded on the same occasions. None of the monitored areas were covered during the monitoring period: they were directly exposed to rainfall and evapotranspiration in open field conditions. The active zone extends to about 1.7 m (Fityus et al. 2004) and the contribution to the surface ground movement of the active clay layer below the injection point is believed to be negligible according the results obtained by Fityus et al. (2004).

The results of the field monitoring study are presented in Fig. 13. They show that, since the time of injection, the ground movements in the injected zone have followed a

Fig. 10. Results of the large swelling tests: evolution of vertical displacement with time.



similar trend to the movement in the nontreated soil and in particular, the injected ground movements lie within the range of movements measured in the noninjected soils. The range of ground movement in the noninjected soils was measured to be 34 mm in zone 1 and 57 mm in zone 2. The range of movement in the injected zone was measured to be 43 mm. More significantly, at no time did the movement in the injected zone — since the time of injection — exceed the movement of at least one of the noninjected zones. The significance of these and the preceeding results will be considered in the following section

Evaluation of the results in the context of possible overlifting

The set of experimental investigations presented in the section titled “Results” provides a sufficient basis to evaluate expanding resin injection as a means of remediating deflected expansive clay foundations. There seems little doubt that expanding polyurethane resin can both lift and support lightly loaded structures whilst restoring foundation levels. The long-term performance of the remediated foundation is, however, less certain. As noted in the “Introduction,” concern exists regarding the lateral confinement provided to a cracked clay soil by injected resins, and there are reasonable grounds to suspect that if the injected soil (with its resin-filled cracks) becomes wetter, that vertical swelling in injected areas will be exacerbated, with undesirable consequences. It remains now to make an overall evaluation of the results of this study and evaluate this risk, and this will be done by answering the questions that were posed in the section titled “Experimental program.”

(1) *How does the resin propagate in the soil mass as it expands?* (see response after question 2 below)

Fig. 11. View of a slice cut in injected specimens (*a*) 1 and (*b*) 3 (diameter: 300 mm).

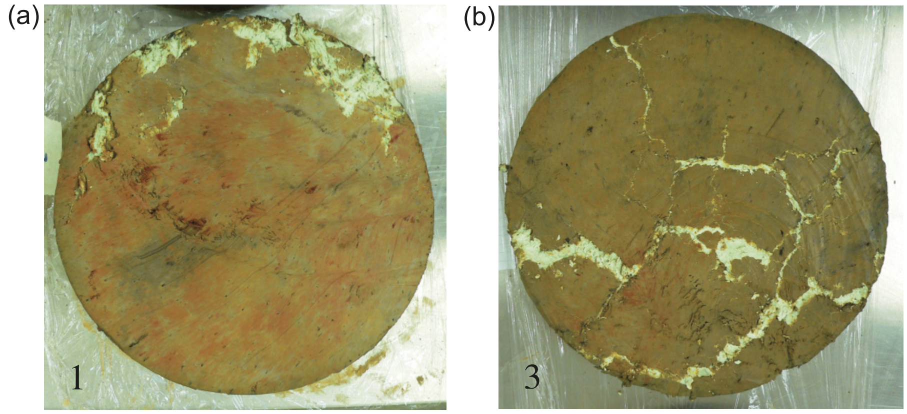
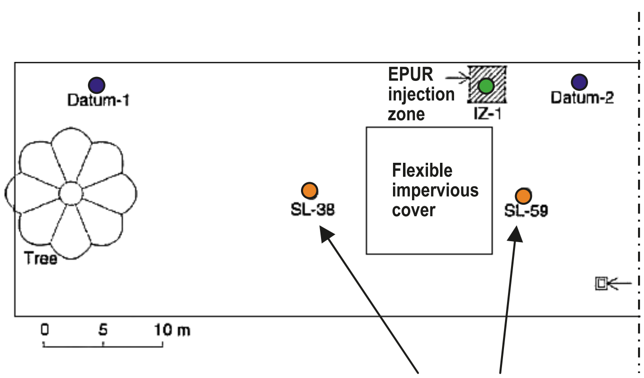


Fig. 12. Partial schematic view of Maryland experimental field site and location of levelling points. EPUR, expanding polyurethane resin.



(2) *What are the structure and properties of the soil–resin composite that is formed?* — The resin propagates by preferentially following pre-existing weaknesses–defects, travelling tens of centimetres through wider cracks, but only centimetres or millimetres through narrower cracks. It does not fill all of the cracks, and the distribution and extent of crack-filling is unpredictable. If the point of injection is below the crack zone, then the extent of crack-filling is significantly reduced.
(3) *How does the resin affect soil rehydration?* — The resin formed in the cracks has a hydraulic conductivity lower than that of intact clay, but it is not totally impermeable. The unpredictability of resin propagation suggests that at least some of the macrovoids of the soil will remain open, and this is confirmed by the in situ permeability measurements: whilst resin injection reduces the macrovoid permeability by a factor of up to 50, the injected soil remains 4–5 times more permeable than the uncracked soil. Consequently, the injected resin will not prevent the soil from rehydrating, but it may make it less susceptible to rapid rehydration.
(4) *Does the presence of resin increase the swelling potential of the soil through the filling of voids?* — Both the results of the large-scale swelling tests and the field monitoring of resin-injected expansive soils indicate that the injected resin does not significantly increase the swelling potential of a cracked expansive soil. This outcome can be justified by considering the nature of swell pressure development in expansive soils. While it is well known that intact clay soils can exert large swelling pressures (up to several MPa) in a fully confined state, it has also been shown that the swelling pressure diminishes rapidly when there are only small reductions in confinement. In the context of a cracked expansive soil, the cracks serve as reductions in confinement, allowing swelling pressure to be relieved as clay swells to collapse the internal voids. Results from the literature, in particular those after Uppal and Palit (1969), have shown that the swelling pressure of expansive soils significantly drops when there is even a small percentage of voids for the soil to expand into before being confined (Fig. 14). The unpredictability (and limited efficiency) of resin-filled cracks in an expansive clay suggests that even after a foundation has been subjected to resin injection to achieve releveling, there are likely to be sufficient unfilled cracks remaining to allow much of the excess swelling potential to be relieved.

If the above justification is considered further, then it is apparent that the risks of overlifting can be reduced by ensuring that a significant proportion of the shrinkage cracks remain in the clay foundation after remediation. In the context of lifting mechanisms 1 and 2, identified in Fig. 6, this suggests that mechanism 2 — injection below the cracks — is likely to lead to an even lower risk of overlifting. As a conclusion, it is considered that injection of expanding polyurethane resin in expansive soil is unlikely to result in significant over-lifting, the risk being reduced further with injection below the cracked zone.

Conclusions

The expanding polyurethane injection technique was developed to remediate differential settlements in foundations beneath structures, and it has found wide application in this regard. Its adoption as a means of remediation for "settled" foundations in expansive soils has proceeded cautiously, due to concerns related to the possibility that swelling in resin-injected soils could be exacerbated if all of the cracks are filled with resin. The possibility of overlifting

Fig. 13. Evolution of surface movement in injected and noninjected zones over a period of 3 years. Monitoring began after injection, on the same day.

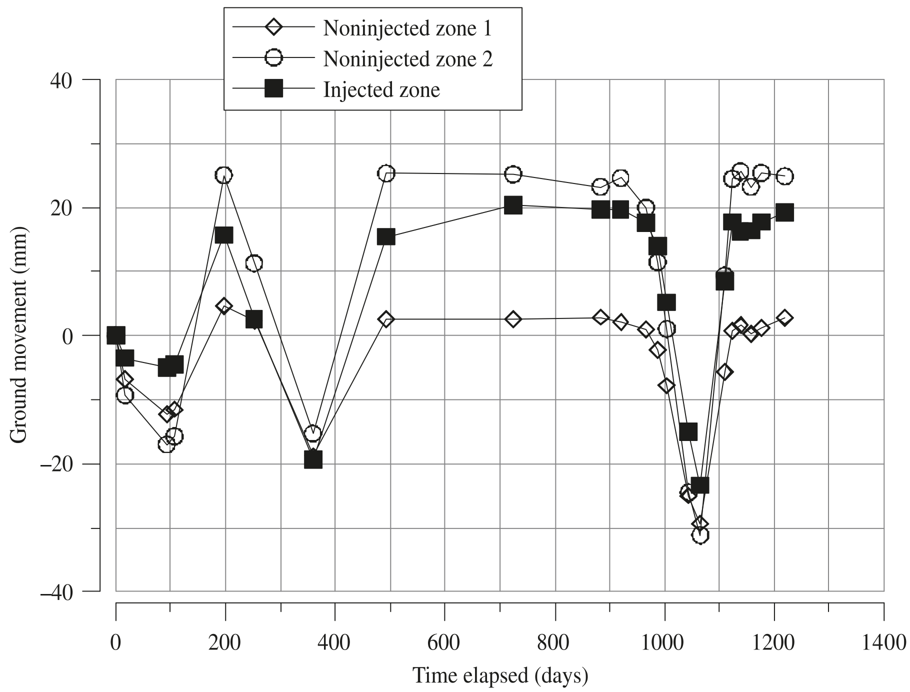
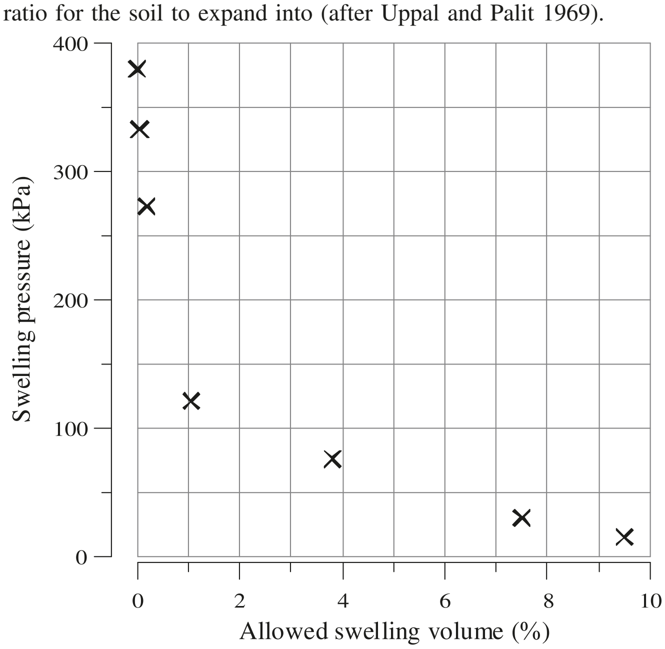


Fig. 14. Reduction in swelling pressure as a function of free void ratio for the soil to expand into (after Uppal and Palit 1969).



due to a resin-injected expansive clay foundation becoming re-wetted has been considered by the series of experimental studies described in this paper. By taking into account the propagation characteristics of injected resin, the structure and distribution of injected resin in a cracked clay soil, the permeability of expanded resins and resin-injected soil masses, and the swelling characteristics of resin-injected soils, the issue of overlifting can now be considered in some detail.

The results of this work have shown that the propagation of resin is relatively unpredictable and that injected resin cannot prevent hydration in an injected soil but can at most delay it. However, the laboratory and in situ tests showed that the resin-injected expansive soil does not exhibit an enhanced swelling potential, probably due to the fact that a significant number of unfilled cracks remain in the injected soil and these provide sufficient relief in the swelling soil to prevent the injected soil mass from swelling excessively. On the basis of this understanding, and the observations of this study, it is suggested that, by injecting deeply (that is, below the depth of cracking), the resin is likely to fill relatively few of the cracks during injection so that a significant amount of voids can still be expected in the soil mass. Consistent with the results of the literature, the swelling pressure of the soil is then expected to be much lower than that usually measured in the laboratory under total confinement.

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