Conceptual model for the remediation of expansive clay foundations using expanding polyurethane resin

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ABSTRACT

Injection of expanding polyurethane resin is a viable alternative to underpinning to correct differential foundation movements in individual houses. When injected into deformed foundations in expansive soils, which may be subsequently subjected to water content increases, it is of particular importance to understand how soil-resin composite material behaves, and especially, what its swelling capacity is. In theory, a building on a treated foundation could be damaged if there is subsequent swelling of treated soil. This paper firstly considers the effect of resin injection on the transfer properties of expansive clay soils, and concludes that resin injection of a cracked clay soil can reduce the macrovoid permeability of by a factor of around 50. It then presents a conceptual analysis of the performance of an expanding polyurethane resin-treated, expansive clay foundation. It discusses the soil structure interaction problem by firstly identifying the key behavioural characteristics of each of the components, and then by considering their likely interaction. It concludes with a discussion of how the soil–structure interaction problem might be formulated and solved.

1 INTRODUCTION

Injection of expanding polyurethane resin (EPR) is now a commonly employed alternative to conventional underpinning, to correct differential deflections in individual houses, buildings and paving slabs. Differential deflections are corrected by the pressure exerted as gasses are produced during the chemical reaction that forms the resin. This solution does not require excavation or the installation of additional foundation elements, since the resin is directly injected under the building using aluminium tubes inserted into small drilled holes.

This approach is well suited to situations where foundation volume changes are due to consolidation or compaction, and hence are irreversible. However, if applied to expansive soils, in which volume changes are potentially reversible, it is of particular importance to understand hydraulic properties and swelling behaviour of the soil-resin composite how the resin may affect the performance of the remediated foundation. This is because the desiccation cracks that form during expansive soil shrinkage are filled with resin, meaning that any future wetting of the soil cannot close the cracks. This could lead to enhanced vertical swelling that could over-lift the remediated foundation. Very little data is available in the literature on this underpinning technique and on the composite polyurethane resin/expansive soil material. Polyurethane resin grouting is mentioned in Vinson & Michell (1972) but other kinds of resin are more common in grouting (e.g. epoxy). Moreover, most grouting techniques are applied to granular soils or fractured rocks, as the grout injection pressure required to permeate a granular material are too great in fine soils (Akbulu & Saglamer 2002).

This paper first presents some experimental observations on the resin and its ability to propagate into a cracked, natural clay. It then presents a conceptual analysis of how an EPR treated expansive clay foundation might perform if it were subjected to excess moisture. This is considered both in terms of how readily water is able to enter the treated soil, and how the treated soil would be affected by water if it entered.

2 THE EXPANDING POLYURETHANE RESIN (EPR)

Expanded polyurethane resin is formed from an exothermic reaction between a polyol and an isocyanate, mixed in specific volumetric proportions. A large amount of carbon dioxide is produced during the reaction; causing the expansion and producing a foam structure where gas bubbles (cells) are surrounded by rigid walls. In the case of EPR this is a closed cell structure. For the foundation remediation application; the resin expands in less than 10 seconds and hardens within one minute. The resin used in this research, when reacted without confinement (free expansion), reaches a volume forty times greater than that of the initial components. When injected into soil, an expansion pressure is developed, and the volume attained depends on the confinement level. Pressures of up to 10 MPa are possible (Favaretti et al. 2004). Once injected, the resin is considered to be stable since it is only degraded by UV radiation and some volatile solvents (e.g. acetone) that should not be found under a building.

3 PROPAGATION INTO THE GROUND

Several undisturbed composite soil specimens have been taken from resin injected areas at the Maryland reactive clay test site (Fityus et al, 2004). Figure 1 shows the composite resin/soil material in case of an injection in silty clay (A) and in a cracked residual clay (B). As explained in Favaretti et al. (2004), the injected resin permeates into the soil following the weakest path. In case of a cracked soil, the resin fills and enlarges the existing cracks. The resin is also observed to enter cracks as small as 0.1 mm although the resin does not penetrate very far in these thin cracks. This phenomenon generates a soil/resin interface visible in Figure 1 (A). This interface is 1 to 3 mm thick and includes a skin on the resin.

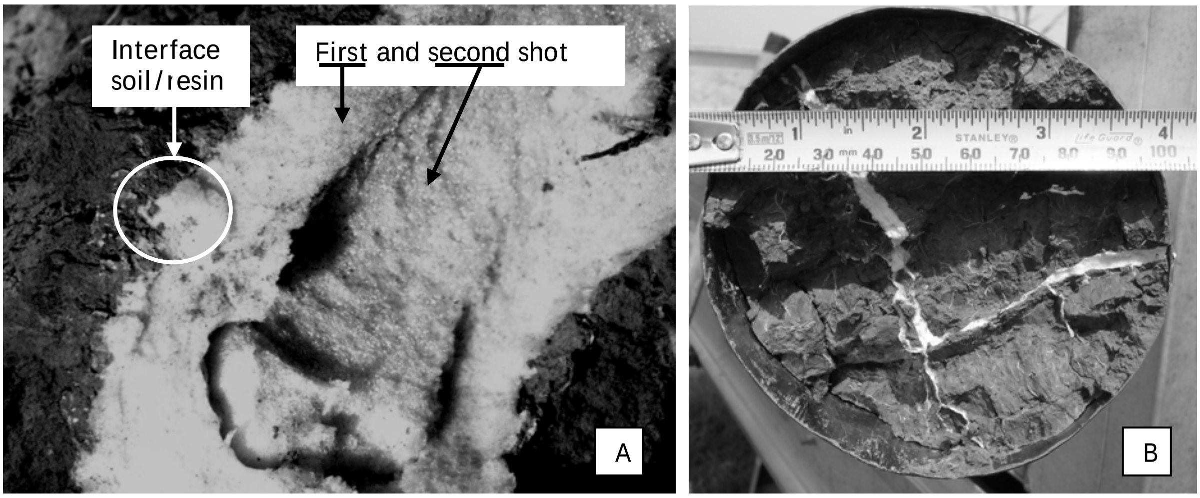

Figure 1: View of soil/resin composite material. (A) Resin injection in silty clay. Width of the resin layer about 20 mm. (B) Resin injection in residual clay.

The resin injection is usually made in multiple ‘shots’, allowing the resin to expand between the shots, so that its lifting effect of each shot can be assessed before the next shot is made. Resin from two different shots can be identified in Figure 1 (A), the second one having cracked and penetrated the first one, which is consequently compressed. Due to the interaction of these several shots, the resin injected into the ground is a heterogeneous material having several layers and some possible macro voids. Figure 1 (B) shows a larger sample and how the resin penetrates into the crack network formed into the soil. The smallest cracks visible in Figure 1 (B) are about 1 mm wide.

4 IMPACT ON THE SOIL TRANSFER PROPERTIES

The relevant permeability to consider for a foundation soil is not that of a basic soil element (ped), but the permeability of the structured 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 & Lytton 1993). Several models of dual porosity or dual permeability have been proposed to capture the possible flow through the soil elements and into the macro voids (e.g. Chertkov & Ravina 2000). When injecting the resin into expansive clay, the permeability of the soil elements is unchanged but the resin fills the macrovoids limiting the major water flow in the cracks and reducing drastically the permeability of the soil mass.

An in situ air permeability testing technique has been used to assess the impact of the resin on the transfer properties of a cracked soil mass. The experimental arrangement, as used by Wells et al. (2006) is shown in Figure 2 (A). Results of the air permeability tests are displayed in Figure 2(B). The resin injection point was located 1 m beneath the surface and tests were performed in the injected zone (permeability K_I) and in a non injected zone (permeability K_{NI}). In this test, the injection pressure is increased progressively and both flow rate and pressure are periodically measured. The slope of the "flow rate-pressure" relationship is proportional to the permeability of the soil mass. The ratio K_{NI}/K_I was found to be 55 at 600 mm depth and 40 at 450 mm depth whereas natural scattering of the results due to the soil heterogeneity corresponds to factor 2 only. It is thus concluded that, the presence of the resin in the cracks drastically reduces the bulk water transfer properties of the soil mass by preventing water from permeating through the cracks. As a consequence of resin injection, the dual permeability characteristics are eliminated, at least locally. An important consequence of this is the extension of the time to saturation of the soil mass and the need for a more significant raining event to saturate the soil.

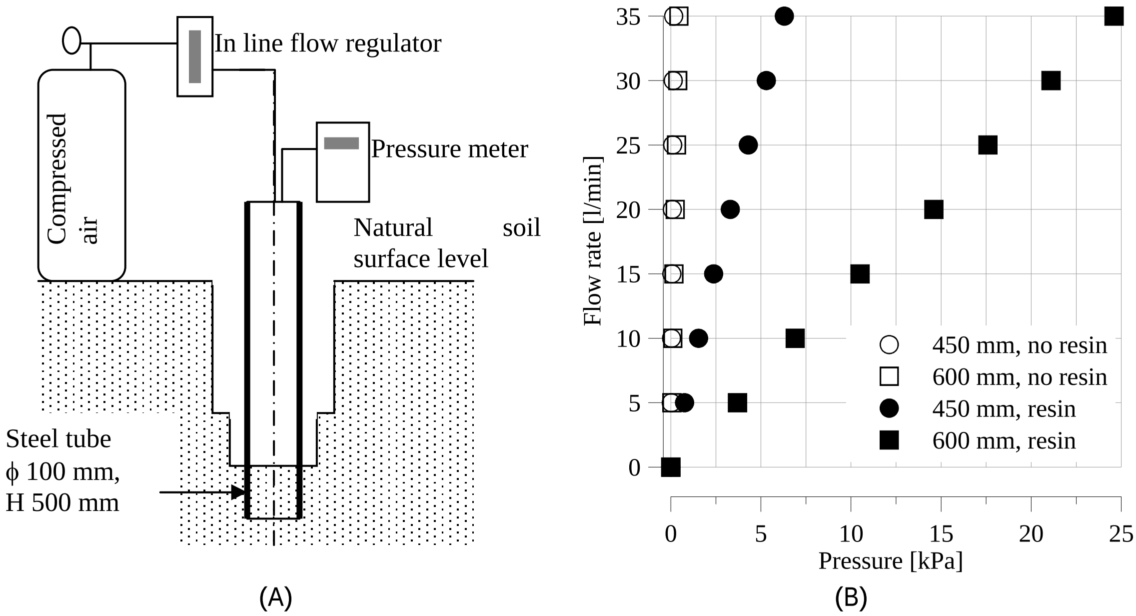

Figure 2: (A) Experimental air permeability device to measure bulk permeability in a structured soil. (B) Results of in situ air permeability measurements in a cracked clay.

5 CONCEPTUAL SOIL-RESIN-STRUCTURE INTERACTION MODEL

5.1 Key Factors

Whether or not an EPR-injected, cracked clay foundation soil will overlift a footing if it becomes wet, is a highly complex problem to analyse. The response of the treated foundation depends on many factors, including the potential for the clay soil to swell subject to a complicated confining arrangement; the capacity of the resin to be crushed by the forces generated by the swelling clay; and the confining load applied by the footing, which varies as localised swelling of clay lifts the footing differentially, causing the contact pressure along its base to become greatly non-uniform.

5.2 Behaviour of the swelling clay

In general, an expansive clay will swell if it is allowed to take up water in a dry state. How much it swells depends on the natural expansiveness of the clay, how dry it is (how much water it can take) and how much stress is acting to suppress the uptake of water and consequent swell. In simple terms, for a given initial water content value, an expansive soil will undergo maximum expansion if inundated in an unconfined state, and it will maintain its volume if a large enough confining stress (greater or equal to its swelling pressure) is applied as it is inundated. For intermediate confining stresses, the soil will experience an intermediate degree of expansion.

If the soil is exposed to a strongly anisotropic stress state, say, full lateral confinement and little or no vertical confinement, then it will swell preferentially in the vertical direction, realising vertical strains in excess of those it would experience if it were expanding freely in all directions. In the case of a desiccated clay in which all of the cracks are filled with EPR, such a condition exists (at least until there is significant compressive strain in the EPR).

5.3 Behaviour of the resin

Although the EPR can exert great pressure during its formation reaction, once it has hardened, it exerts no more load than the stress conditions that exist in the soil around it. In fact there is some evidence to suggest that it may shrink (very slightly) after hardening, thus lowering its stress state.

The EPR resin used in this study displays a response to compressive stresses that is reasonably approximated as linear elastic-plastic. That is, it deforms as a relatively high stiffness elastic material up to some yield stress vale, beyond which it plastically deforms to large strains without attracting a significantly greater load.

5.4 Behaviour of the structure

According to Walsh & Cameron (1997), the typical Australian house loading ranges from 10 kPa to 50 kPa. These are fairly modest values, but in general, they act uniformly over large areas. Compared to the expansion pressures of the EPR or the swelling pressure that can be exerted by typical expansive clay, these are very low. Consequently, the pressure exerted by a uniformly supported foundation is well short of that needed to completely suppress the swelling of underlying clays, or to redirect vertical swelling stresses to act laterally and crush the resin ins the cracks.

Compared to other components in the system, the footings and the superstructure are very stiff. The tall vertical walls of masonary structures are very stiff and do not bend, however, if enough bending stress is applied, they will break. The footings themselves are relatively stiff and bend very slightly. The action of the composite structure is complicated by the presence of a damp proof course that effectively debonds the structure from the footing. Muniruzzaman (1997) performed a series of experimental tests on a full-scale structure (brick wall plus foundation) to investigate the response of the wall to different ground movements. As in many Australian houses, the structure tested incorporated a damp proof course over the two first brick layers. This is of particular importance since it allows a gap between the foundation and the wall, in case of ground movements where a rise at one or both ends produces a dished deflected shape (Figure 3). Consequently, an arching effect is created, whereby the house spans between the ends of the footing and its loading is redistributed as is indicated in Figure 3.

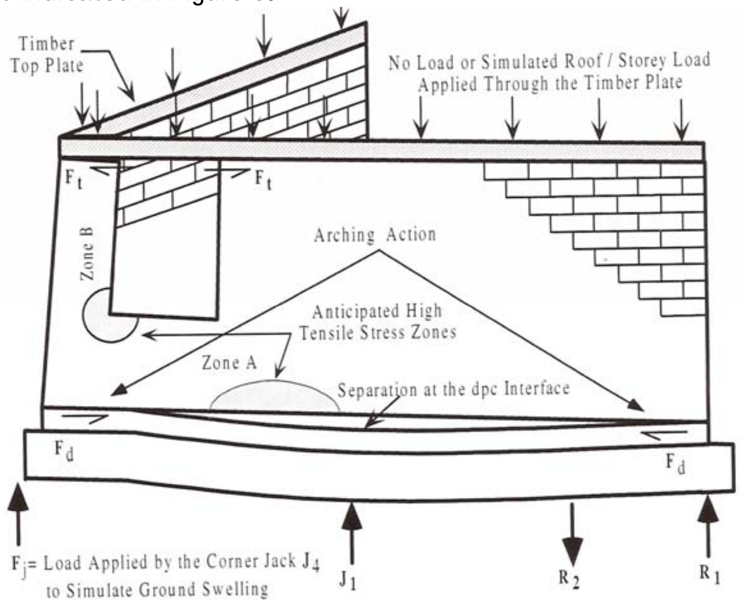

Figure 3: Response of a masonry structure to differential foundation deflections. (after Muniruzzaman, 1997).

The load distribution for the footing is very complicated, depending not only on its irregular contact with the structure, but also, on its contact with the foundation soil. In a worst case scenario, soil becomes locally wet (say, from a leaking pipe) at an extreme end of the footing, so that the area of the swelling is very localised. This is the worst case, since more extensive wetting produces more uniform swelling and lifting, and the span between contact points with the soil is reduced, leading more to a tilting action than a bending action. Figure 4 presents a schematic illustration of 4 stages of deflection in a footing due to localised swelling beneath the left-hand end. As the left-hand end is lifted from a condition of uniform support (condition 1), the central portion begins to lift-off the foundation, over a distance (d_L) that increases with increasing differential rise of the left-hand end (conditions 2-4). The share of the load that is no longer carried by the interval d_L is redistributed to either end of the footing, increasing the pressure over the contact area above the swelling clay, d_c. As the distance d_L increases ($d_{L2}<d_{L3}<d_{L4}$), the pressure on d_c increases, increasing the vertical stress on the swelling clay, and hence, suppressing further swelling.

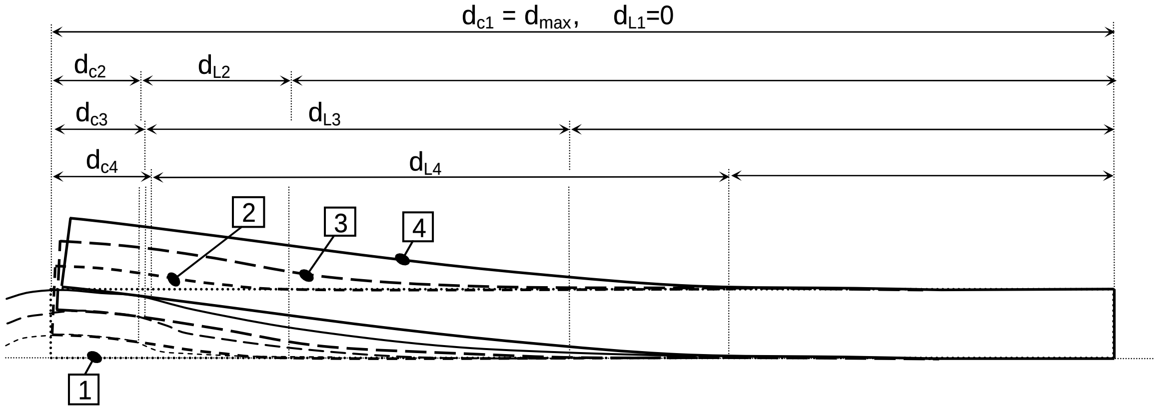

Figure 4: Schematic representation of a footing as it is increasingly deflected at its left-hand end. The contact area increases only slightly, while the lift-off area increases significantly, distributing load back to the contact area.

5.5 Crux of the problem

In light of the above discussion, it is apparent that the issue that must be addressed in contemplating the use of EPR in expansive soil foundations is: *will the redistributed stress to the swelling clay become great enough to suppress any further swelling, or cause the EPR to yield, before the structure reaches a differential deflection sufficient to cause structural damage*?

5.6 Solving the problem

Obtaining the answer to this question is a formidable task. For any specific case, it could be obtained from the development of a non-linear finite element model that can model the footing as a beam or raft, with distributed structural loads acting upon it. Some simplification is afforded by assuming that the structure will remain uncracked and lift at the dampcourse due to arching, effectively causing it to bear at either end of the footing.

The foundation soil model used for the soil-resin composite will need to be considerably more evolved than the Winkler model commonly employed in structural analyses. It will need to account for a non-linear (possibly semi-logarithmic) relationship between confining stress and soil volume. It will also need to accommodate anisotropic elasto-plastic behaviour, so that under realistic combinations of vertical and lateral stress, it will expand or compress in the vertical direction, or yield in the lateral direction, to account for the behaviour of the resin in the composite. Work is progressing on the formulation of such a finite element model.

Work is also underway on simpler approaches to addressing this problem. On the scale of a cracked natural soil, there is merit in modelling the composite, not as a continuum, but as an inhomogenous arrangement of soil elements and resin elements, each with its own mechanical behaviour. A preliminary model to describe the behaviour of swelling soil elements has been proposed by Buzzi et al. (2007).

6 CONCLUSIONS

The determination of when EPR can be used to treat deflected expansive soil foundations without adverse effects is a complex problem. With increasing knowledge and experience of the fundamental behaviour of the resin, the soil and the resin-soil composite, it is possible to formulate a conceptual model of treated foundation behaviour, which will hopefully be implemented in the near future.

The discussion provided in this paper indicates that the likelihood of a treated clay foundation becoming wet through short-term exposure to water, such as runoff from a storm event, is significantly reduced by the reduction in the permeability to bulk water that is achieved by the filling of cracks and macropores with resin. The likelihood of the treated foundation becoming wet through prolonged exposure to excess soil moisture is not considered here, but is being addressed in other aspects of this research.

The discussion provided here also indicates that it is likely that EPR injection can be used to remediate deflected foundations, at least under certain conditions, and that a methodology for determining what those conditions are is achievable.

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