MITIGATION OF LIQUEFACTION-INDUCED DIFFERENTIAL SETTLEMENT BY STABILIZED GRAVEL RAFTS

A. Lees

ABSTRACT

While guidance documents for both California and New Zealand already recommend geogrid-stabilized gravel rafts as a shallow ground improvement method to mitigate liquefaction-induced settlement, they lack a design method to tailor the solution to site-specific conditions. This paper addresses that need by describing, together with a worked example, a design method based on a recently-developed and applied design method for geogrid-stabilized working platforms. The fundamental relationships employed in this design method are also used to demonstrate the geogrid-stabilized gravel raft’s primary mechanism of significantly slowing the decay of bearing capacity as the underlying soil liquefies and weakens.
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While guidance documents for both California and New Zealand already recommend geogrid-stabilized gravel rafts as a shallow ground improvement method to mitigate liquefaction-induced settlement, they lack a design method to tailor the solution to site-specific conditions. This paper addresses that need by describing, together with a worked example, a design method based on a recently-developed and applied design method for geogrid-stabilized working platforms. The fundamental relationships employed in this design method are also used to demonstrate the geogrid-stabilized gravel raft’s primary mechanism of significantly slowing the decay of bearing capacity as the underlying soil liquefies and weakens.

Introduction

Liquefaction of soils supporting shallow foundations leads to severe loss of bearing capacity. This in turn leads to significant foundation settlement which is often non-uniform thus causing extensive structural damage, as reported in several recent earthquakes, most notably the Canterbury Earthquake Sequence (CES) [1] and in other recent earthquakes as summarized by Bray and Dashti [2].

Usually, resilience to such events is incorporated into foundation design by neglecting the superstructure and estimating settlements for free-field conditions. However, it is increasingly recognized that soil-structure interaction plays an important role in the generation of liquefaction-induced settlements [3] and new design methods have been proposed [4].

Ground improvement techniques are commonly employed to mitigate liquefaction-induced settlement and these fall broadly into two categories, namely deep and shallow techniques. The deep techniques, such as rammed aggregate piers [5], reduce the liquefaction potential of soil deposits to depths of several meters and are suited to cases where severe liquefaction events and lateral spreading may need to be prevented. The shallow techniques establish a non-liquefiable crust that help prevent surface manifestations of liquefaction [6] as well as increasing bearing capacity. They are more economical than the deep techniques and tend to be used to prevent less severe liquefaction events and to mitigate differential settlement in housing and other lightly-loaded structures. Following the CES, a large-scale trial [7] of ground improvement techniques

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was undertaken for the Earthquake Commission (EQC) in 2013 to assess performance in reducing the settlement of shallow foundations supported by loose sand deposits subjected to blast-induced liquefaction. One of the techniques trialed included a geogrid-stabilized gravel raft which will be considered in detail in this paper. In particular, a new design method is proposed based on an existing working platform design method and recent research work into soil-structure interaction effects and liquefaction-induced settlement.

Geogrid-stabilized gravel rafts

The EQC ground improvement trials included a gravel raft stabilized with a triangular aperture punched and drawn polypropylene (PP) geogrid. It proved to be effective at reducing the damaging differential settlements and was adopted as a recommended ground improvement method in the New Zealand’s Ministry of Business, Innovation and Employment’s (MBIE) Technical Guidance [8].

Stabilization is a geogrid function recognized as separate from a reinforcement function. It has been defined as “the beneficial consequence on the serviceability of an unbound granular layer via the inhibition of the movement of the particles of that layer under applied load” [9]. The stabilization function at particle scale is best illustrated by the SmartRock™ output from the test set-up shown in Figure 1 [10]. SmartRocks are 3D-printed representations of aggregate particles containing wireless accelerometers such that their position and orientation in space can be recorded in real time. In the rail ballast box set-up, a SmartRock was placed at 0.25 m depth below the end of a tie, with a triangular aperture, punched and drawn PP geogrid also at 0.25 m depth. The rail was subjected to a sinusoidal load cycling between 0 and 130 kN at 1 Hz for 500 cycles. A second identical test was carried out with no geogrid included. The geogrid restrained the SmartRock against translation and, more significantly, rotation as shown in Figure 2. This affects the mechanical properties of the soil in a way that cannot be explained by the traditional geogrid functions.

![Figure 1. Ballast box test set-up with SmartRock.](image-url)
The restraint against translation and rotation of the soil particles in and around the geogrid apertures adds shear strength to the soil. This is illustrated in the very large triaxial compression test data shown in Figure 3 comparing the shear strength recorded in a 40 mm maximum particle size, compacted, well-graded crushed diabase rock with and without a single layer of triangular aperture, punched and drawn PP geogrid placed at mid-height. The specimen dimensions (1.0 m high x 0.5 m diameter) were sufficiently large to significantly reduce boundary effects and to form a representative area of geogrid to interact with the aggregate. As expected, the presence of the geogrid imparted a significant additional shear strength to the soil. Furthermore, the peak strength was maintained for significantly greater strain than in the unstabilised soil, giving the stabilized soil far superior performance at higher strain levels, which is particularly relevant in large strain, strong motion earthquake events.

The stabilization effect of geogrid can thus be represented as an enhanced shear strength in a soil-geogrid composite. In finite element analysis (FEA) models using Mohr-Coulomb failure criteria, the additional strength can be represented as apparent cohesion $c'$. Since stabilization diminishes with distance from the geogrid, it can be represented as a $c'$-profile with its maximum at the geogrid plane and reducing linearly with distance from the geogrid plane to zero stabilization at, typically, about 0.3 m distance above and below the geogrid. This method was found to give significantly more accurate simulations of plate load tests on geogrid-stabilized layers compared with the conventional method of using membrane elements with tensile stiffness to represent geogrid [11].

On liquefiable soils, the gravel raft provides a non-liquefiable crust on which to construct shallow foundations which helps to prevent soil ejecta reaching the surface if the underlying layer liquefies. A geogrid-stabilized gravel raft also significantly enhances bearing capacity and, as a
result, reduces shear-induced settlement mechanisms such as punching failure and soil-structure interaction ratcheting [4].

Calculation of the bearing capacity of a granular layer overlying a weaker soil arises often in foundation design. Different methods exist, perhaps the most commonly used being the semi-empirical Hannah and Meyerhof [12] method and the load spread method, as summarized by Craig and Chua [13]. The drawbacks of these methods include the difficulty of determining key parameters defining the complex interaction between the layers and including the effects of stabilization of the granular layer. Many studies [14,15,16] have shown the significantly improved bearing capacity brought by geogrid stabilization yet no reliable, simple method of its calculation has been forthcoming.

Lees [17] addressed this need by identifying an approximately linear relationship between dimensionless bearing capacity \( q_u/q_s \) and geometrical \( H/B \) ratios (where \( q_u \) and \( q_s \) are the bearing capacity of the layered system and subgrade alone respectively, \( H \) is the granular layer thickness and \( B \) is the foundation width). The slope of the linear relationship was called the load transfer efficiency \( T \) which can be determined by full-scale testing and parametric study by numerical analysis and is specific to a particular geogrid-soil combination. It was found to vary exponentially with subgrade shear strength as shown for the centrifuge test data [18] for strip and circular surface footings on a sand layer overlying clay in Figure 4. This method was developed for and is now applied in the design of geogrid-stabilized working platforms used to support tracked plant such as piling rigs and mobile cranes.
Taking a typical case of a 0.9 m square pad foundation on the surface of a 1.2 m thick granular layer overlying a subgrade of undrained shear strength $c_u$, as shown in Figure 5, the ultimate bearing capacity $q_u$ at the surface can be calculated for a non-stabilized and geogrid-stabilized granular layer at different $c_u$ values and compared with the bearing capacity $q_s$ directly on the subgrade as shown in Figure 5. While $q_s$ falls linearly with shear strength, the gravel raft takes a non-linear path. As the subgrade shear strength becomes weaker, the ratio $q_u/q_s$ increases due to the greater efficiency of the gravel raft – even more so for the geogrid-stabilized case. If the $c_u$ values were residual values following liquefaction of the subgrade, this graph shows that when the subgrade liquefies and becomes weaker, the bearing capacity ratio of the stabilized gravel raft increases. Or, to look at it another way, the decay of bearing capacity as the subgrade weakens is much slower. This would help to explain the excellent performance of the geogrid-stabilized gravel raft in the NZ trial and as noted from site observations following earthquakes in the CES [19].
Guidance on the specification of geogrid-stabilized gravel rafts is provided in the Alameda County guidelines [20] and MBIE guidance [8] as summarized in Figure 6. They differ slightly in the recommended depth of the gravel raft and its width relative to the building footprint. The drawback of this guidance is that it offers only nominal dimensions with no design method to demonstrate sufficient reliability under a given set of conditions (e.g., earthquake magnitude, building load, foundation depth, residual shear strength, etc.). The following section of this paper addresses this need by presenting a design method based on the working platform bearing capacity method described earlier.

Figure 6. Existing guidance on geogrid-stabilized gravel raft specification.

**Design method**

Bray and Macedo [4] performed an extensive parametric study using the finite difference method, validated by site observations and centrifuge testing, of the liquefaction-induced settlement of shallow-founded buildings on liquefying soil. They varied the thicknesses of the non-liquefiable crust, liquefiable layer and underlying non-liquefiable layer, as well as liquefiable layer relative density, foundation contact pressure, building height and width and imposed 36 different recorded earthquake motions. They added the shear-induced building settlement output to the calculated free-field consolidation settlement to obtain the total liquefaction-induced settlement and found that in cases where the factor of safety on static bearing capacity was in excess of 1.5, total settlements were generally less than 100mm, as shown for one of the earthquake motions in Figure 7. Indeed, the first step of their proposed design method for estimating liquefaction-induced settlement was to check the factor of safety on static bearing capacity with residual soil strength estimated from site investigation information such as piezocone data.
Furthermore, SP117A [21] recommends a factor of safety on bearing capacity of at least 1.5 to help avoid large foundation settlements on liquefied soil and the Los Angeles Manual [22] states that structural mitigation only is acceptable for a total settlement of up to 4″ (100mm), both of which would be satisfied by this new approach. The Los Angeles Manual also requires a differential vertical settlement of up to 1″ measured over a horizontal distance of 30′ (9 m). Differential settlement is even more difficult than total settlement to estimate but SCEC [23] concludes that differential settlements on level ground with natural, relatively uniform soil conditions are likely to be small even if total settlement is large, but in the absence of extensive site investigation a minimum differential settlement of one-half the total settlement can be assumed. Therefore, depending on the amount of site investigation information and variability of soil conditions, a higher factor of safety than 1.5 on static bearing capacity may be selected to meet the differential settlement requirements. Note that the Bray and Macedo total settlements were calculated by summing the free-field and shear-induced values whereas the Los Angeles Manual requirements are based on the free-field settlement only. Alternatively, advanced numerical analysis techniques can be employed to estimate the reduction in differential settlement resulting from the inclusion of a stabilized gravel raft.

Therefore, the proposed design method for gravel rafts to mitigate liquefaction-induced settlement is to obtain a factor of safety on bearing capacity in excess of 1.5 using the analysis method developed for stabilized working platforms. The subgrade shear strength is substituted for the liquefied soil residual undrained shear strength estimated using well-established methods, e.g. [24].

As explained earlier, the $T$ values for the gravel raft are obtained by parametric study using numerical analysis validated by full-scale, large plate load testing to bearing capacity failure. Input parameters to the numerical analyses are obtained by large triaxial compression tests on the proposed aggregate forming the gravel raft. A geogrid product can be included in the triaxial specimen to obtain the stabilized soil properties with that specific geogrid product. Note that the geogrid tensile strength and stiffness are not an input parameter to this method, rather the effect of...
the geogrid on the soil is measured and simulated in the numerical analysis.

A design example for a typical house strip foundation is presented in Figure 8. The relationships between $T$ and subgrade shear strength were derived for a well-graded crushed stone of up to 40 mm particle size, with and without one type of triangular punched and drawn PP geogrid denoted “Geogrid A”. For a strip foundation ($B/L=0$), $T$ values of 3 and 1 for the stabilized and non-stabilized cases respectively were obtained. This resulted in a calculated gravel raft thickness of 0.9 m with Geogrid A at 0.25 m centers, or a significantly thicker 2.7 m in the unstabilised gravel raft case.

$$\frac{q_u}{q_s} = 1 + T\frac{H}{B} \leq \frac{q_g}{q_s}$$

$$\frac{150 \times 1.5}{(5.14 \times 5) + 10} = 1 + 3\frac{H}{0.5} \Rightarrow H \approx 0.9 \text{ m}$$

Figure 8. Geogrid-stabilized gravel raft design example.

Conclusions

Dimensionless relationships adopted in a recently-developed design method for geogrid-stabilized working platforms were found to provide a plausible explanation for the efficient performance of geogrid-stabilized gravel rafts in mitigating liquefaction-induced differential settlement in a full-scale trial and in recent case studies. As the subgrade becomes weaker, the load transfer efficiency $T$ of the stabilized gravel raft increases exponentially thereby significantly slowing the decay of
bearing capacity in the gravel raft as the underlying soil liquefies. Geogrid-stabilized gravel rafts are already a recommended shallow ground improvement method for housing and lightly-loaded structures in existing guidance documents in both California and New Zealand but for the first time a design method has been developed to demonstrate performance and to tailor the solution to site-specific conditions. The method utilizes a recent research finding that liquefaction-induced building settlements of more than 100 mm are unlikely to occur when the factor of safety on static bearing capacity of the foundations on residual strength liquefied soil is at least 1.5. This factor of safety can be calculated for geogrid-stabilized gravel rafts using the working platform design method described in this paper. Adoption of the method requires the relationship between load transfer efficiency \( T \) of the gravel raft and undrained subgrade shear strength to be derived by parametric study using numerical analysis validated by full-scale testing to bearing capacity failure. The mechanical properties of the stabilized soil are measured by very large triaxial compression testing on the soil-geogrid composite and do not depend on the “in-air” tensile properties of the geogrid.

References


