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Ultimate Pullout Capacity of Granular Pile Anchors in Homogenous Ground

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Key words

Granular pile/Stone column, Granular pile anchor (GPA), Homogeneous ground, Ultimate pullout capacity, Critical length.

Abstract: Granular piles (GP) well known for their ability to transfer compressive loads to the ground cannot resist tensile or pullout loads because of the inherent nature of granular materials. However, granular pile can be made to resist pullout forces by a simple modification of providing a pedestal/geogrid/metallic plate at the bottom and attaching a cable or a rod to the same to transmit the pullout or uplift load. Granular pile with a plate at the bottom that is connected to the footing through a cable or rod is termed as Granular Pile Anchor (GPA). The paper presents a method for the estimation of the ultimate pullout capacity of GPA in homogeneous (constant undrained strength) ground conditions as the lesser of the two values obtained considering pile and bulging failure mechanisms. The ultimate pullout capacity and the critical length of GPA corresponding to a transition from pile to bulging failure are evaluated as functions of various parameters such as the length to diameter ratio, L/d, of GPA, the ratio of the shear modulus to undrained strength, G/c_u, of the ground, the undrained shear strength of soil, c_u, and unit weight, γ_{gp} and the angle of shearing resistance, ϕ_g, of the granular pile material, lateral coefficient of earth pressure, K_0, etc. The predicted ultimate capacities compare well with those obtained from limited available experimental results.

Introduction

Stone Columns/Granular Piles (GP) are most preferred over various other methods of ground improvement because of their ability to improve the performance of soft soils, loose sand deposits and waste fill sites. The performance of the ground is improved by reinforcement, densification and drainage effects through increase in bearing capacity, reduction in settlements, acceleration of the rate of consolidation. GPs are installed in wide variety of soils, ranging from loose sands to soft clays and organic soils using vibro-replacement, composer (sand compaction piles), rammed stone columns and even by heavy tamping techniques.

Granular piles functioning as drains improve liquefaction resistance of loose sands and minimize settlements following a seismic event (Seed *et al.,* 1976; Seed & Booker 1977; Madhav & Arlekar, 2000). No damage was observed from sites treated with stone columns and subjected to the Loma Prieta earthquake (Mitchell & Wentz, 1991). Granular piles mitigate the potential for liquefaction and damage by (i) preventing build up high pore pressure; (ii) providing drainage path and (iii) increasing the strength and stiffness of ground. Granular piles reinforce the ground and enhance the stability of embankments founded on them (Sabhahit *et al.,* 1997). Granular piles are efficient in transferring loads from a heavy structure (Wissmann and Fox, 2000a and Wissmann *et al.* 2000b). Thus while GP improve, strengthen, stiffen and modify the performance of soft ground through compression and shear resistances, their potential to offer pullout resistance has not been fully explored or exploited.

Methods for Granular Pile Construction

Various methods for installation of granular piles such as vibro-compaction (Baumann & Bauer, 1974; Engelhardt & Kirsch, 1977), vibro-compozer (Aboshi *et al.* 1979; Aboshi & Suematsu, 1985; Barksdale & Bachus, 1983), cased-borehole and vibro-replacement, etc., have been used all over the world depending on their proven applicability and availability of equipment in the locality. Ohbayashi *et al.* (1999) report significant improvement in the values of coefficient of lateral earth pressure, K_0 subsequent to installation of sand compaction piles (Figure1).

Conventionally granular piles/ stone columns, due to their inherent nature, cannot resist pullout/tensile forces. However, by placing a concrete pedestal, a metallic plate or a geogrid at the bottom and connecting it to the footing with a cable or a rod, (Figure 2) pullout forces can be transmitted to the base of the granular pile to resist pullout or uplift forces. Such foundation elements are termed variously as Granular Pile Anchors (GPA), Anchored Granular Pile (AGP) or Granular Anchor Pile (GAP). The first terminology is adopted in this paper. The concept of using anchored granular piles to resist heave was studied by Phani Kumar *et al.* (2000 & 2004), and Sharma and phani kumar (2005). Kumar *et al.* (2003), Setty *et al.* (2000) and Ranjan and Kumar (2000) report studies on

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response of granular anchor piles to compression and uplift. Application of short aggregate piers for resisting uplift and controlling the settlements for various structures subjected to high uplift forces and numerical validation of the same was presented by Lawton *et al.* (1994). A similar study on uplift capacity of GPA was reported by White *et al.* (2001) and Lillis *et al.* (2004).

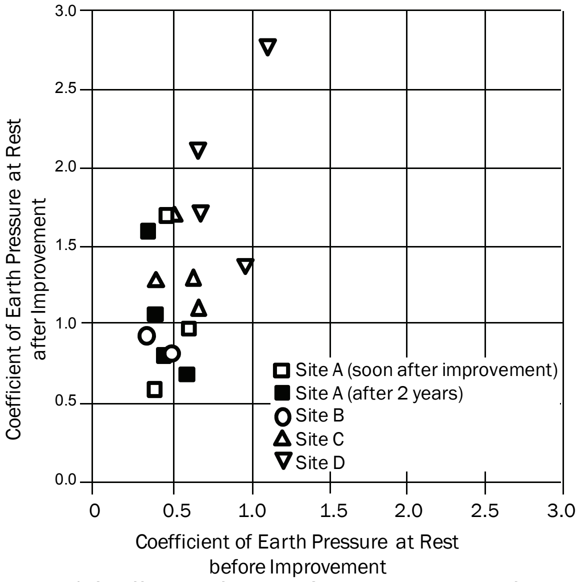

Fig. 1 Coefficient of Lateral Stress at Rest, K_0, after Improvement (after Ohbayashi et al. 1999)

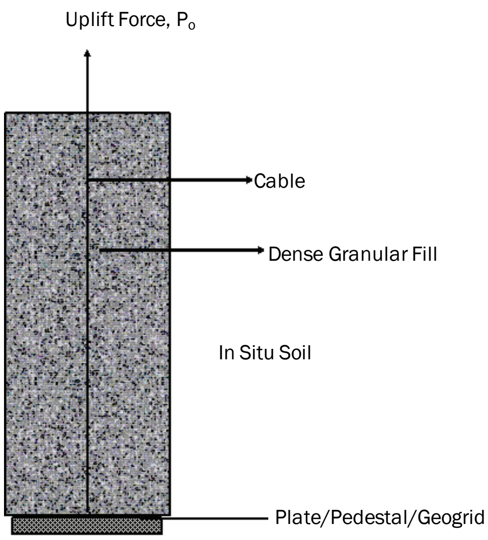

Fig. 2 Granular Pile Anchor

Ultimate Pullout Capacity of Granular Pile Anchor (Gpa)

A Granular Pile Anchor (GPA) of length, L, and diameter, d, is considered (Figure 3). The saturated unit weight, undrained strength and shear modulus of the in situ soil assumed constant with depth (Figure 3b), are γ_s, c_u and G respectively while ϕ_g and γ_{gp} are respectively the angle of shearing resistance and the unit weight of the granular pile material. The ultimate pullout capacity

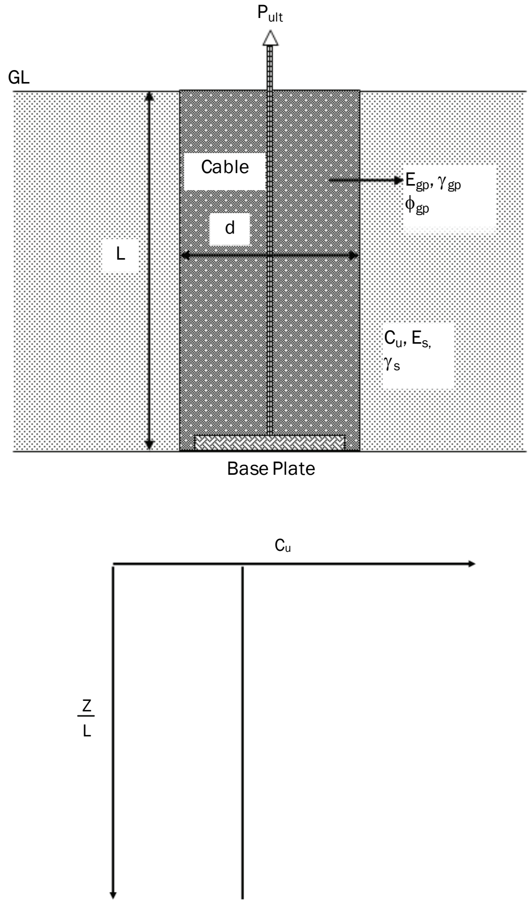

Fig. 3 Definition Sketch (a) GPA under Pullout (b) Undrained Strength Profile

of the GPA is the load at which it is either pulled out by failure of the bond between the granular pile and the soil surrounding it, i.e., pile (Figure 4a) or by bulging (Figure 4b) failure. The ultimate pullout capacity, P_{ult}, of GPA is obtained for homogeneous undrained soil conditions (Figure 3b) as the lesser of the two values obtained as above.

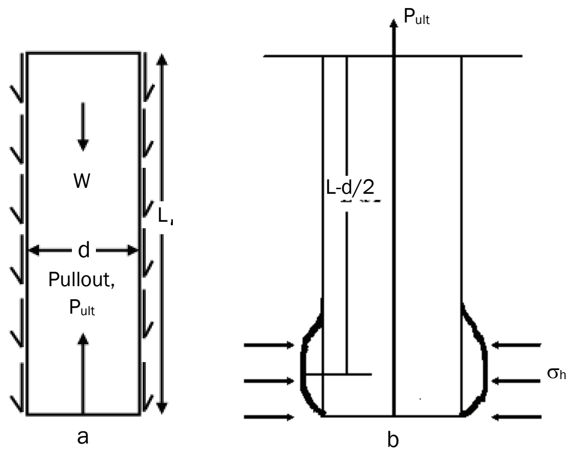

Fig. 4 (a) Pile Failure and for GPA in pullout (b) Bulging Failure Mechanisms for GPA in pullout (Hughes & Withers, 1974; Hughes *et al.,* 1975)

For pile failure, the pullout capacity, P_{ult}, is limited by the shaft resistance that equals the undrained strength, c_u, of the in situ soil acting along the periphery of the GPA along with the weight of the granular pile material acting downwards. That is

$$P_{ult} = \pi.d.L.c_u + \frac{\pi.d^2}{4}.L.\gamma_{gp} \quad (1)$$

The normalized ultimate pullout load, P* is

$$P^* = \frac{4P_{ult}}{\pi d^2 c_u} = \frac{L}{d}(4+\lambda) \quad (2)$$

where $\lambda = \frac{\gamma_{gp}.d}{c_u}$

For bulging failure, following Gibson and Anderson (1961), Hughes & Withers (1974) and Hughes *et al.* (1975), expansion of a cavity near the bottom (at a distance of d/2 from the tip) of the GPA is considered and P_{ult} estimated as,

$$P_{ult} = \frac{\pi.d^2}{4}.N_\phi\left\{c_u.N_c^* + \sigma_{h_o}\right\} \quad (3)$$

where $N_\phi = (1+\sin\phi_g)/(1-\sin\phi_g)$, $N^*_c = 1 + \ln(G/c_u)$ - a bearing capacity factor. The total horizontal stress, σ_{h0}, at depth z = (L-d/2) assuming groundwater level to be at ground level is

$$\sigma_{h_o} = \left\{\gamma_{sub}.K_o + \gamma_w\right\}(L - \frac{d}{2}) \quad (4)$$

where K_0 - lateral earth pressure coefficient at rest and γ_{sub} – the submerged or buoyant unit weight of the soil. The normalized ultimate pullout load by bulging, P* is

$$P^* = \frac{4P_{ult}}{\pi d^2 c_u} = N_\phi\left[N_c^* + \beta.\left(\frac{L}{d} - \frac{1}{2}\right)\right] \quad (5)$$

where $\beta = \frac{\gamma_w d}{c_u}\left(K_0\alpha + 1\right)$ is lateral confining pressure coefficient and $\alpha = \frac{\gamma_{sub}}{\gamma_w}$.

Bulging is considered likely to occur at a distance of half-diameter of the GPA but from the tip instead of from the top as is considered for bulging capacity of granular piles in compression. The pullout capacities of the GPA by pile and bulging failures equal at a particular value of L/d termed as the critical length ratio, $(L/d)_{cr}$.

Results

The ultimate pullout resistance of GPA is estimated for both the pile and bulging failure mechanisms using Equations (2) & (5) respectively for the following ranges of the parameters: γ_s: 14 to 16 kN/m^3; γ_{gp}: 18 to 21 kN/m^3; c_u: 10 to 60 kPa; L/d: 1 to 25; ϕ_g: 30^0 to 45^0; G/c_u: 50 to 500; $\gamma_s d/c_u$: 0.1 to 2; λ (=$\gamma_{gp}d/c_u$): 0.1 to 2.5; $\gamma_{sub}d/c_u$: 0.03 to 0.7; $\gamma_w d/c_u$: 0.08 to 1.2, α =0.4 - 0.6, β = 0.1 - 1.6 and K_0=0.5-1.0.

The normalized ultimate pullout capacity of GPA, P* (=$4P_{ult}/\pi d^2 c_u$) increases (Figure 5) with L/d for both pile and bulging mechanisms with increasing L/d and G/c_u. The results are plotted for angle of shearing resistance, ϕ = 35^0, λ= 1.3 and β = 1.0. The ultimate pullout capacity of GPA by pile failure mechanism increases linearly with L/d ratio as for rigid piles. The pullout capacity of GPA by bulging not only depends on

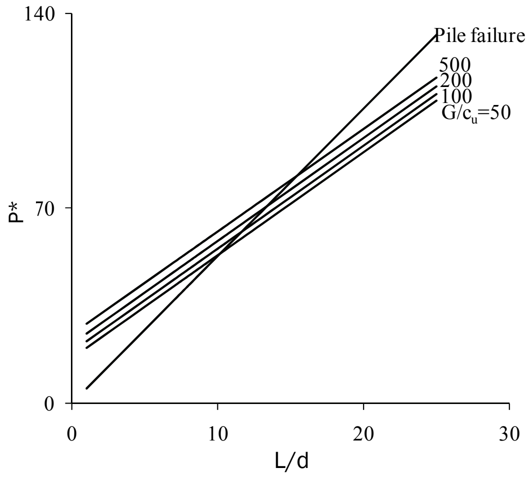

Fig. 5 Variation of Pullout Capacity P* of GPA with L/d (effect of G/c_u for ϕ=35^0, λ=1.3 & β = 1.0)

G/c_u and ϕ_g but also on L/d unlike in the case of granular piles under compression, as bulging takes place near the tip, the point of application of load increasing with increasing L/d ratio of GPA. The rate of increase of ultimate pullout capacity, P*, with L/d is more for pile failure than that for bulging failure. The ultimate pullout capacity by pile failure is less than the capacity by bulging for L/d < 8 to 10 for G/c_u increasing from 50 to 500. This effect is due to the fact that ultimate capacity of GPA by bulging failure depends on both L/d and G/c_u, while that by pile mechanism is dependent on only L/d. The ultimate pullout capacity of GPA is controlled by bulging failure for long GPA as is the case with granular piles in compression. The ratio G/c_u affects the pullout capacity of the GPA marginally. The normalized pullout capacity of the GPA increases from about 105 to 115 for L/d =25 for a ten-fold increase in G/c_u from 50 to 500 as this ratio affects the bearing capacity factor, N^*_c, only marginally.

The variation of P* with L/d for different angles of shearing resistance of the granular material, ϕ_g, and with G/c_u of the in situ soft soil (Figure 6) for β=1.0 and λ=1.3 shows that the ultimate pullout capacity of GPA by bulging failure is strongly dependent on the shearing resistance of the granular material, ϕ_g. P* increases by nearly two-fold, i.e. from about 45 to 85 for angle of shearing resistance of the granular material, ϕ_g,

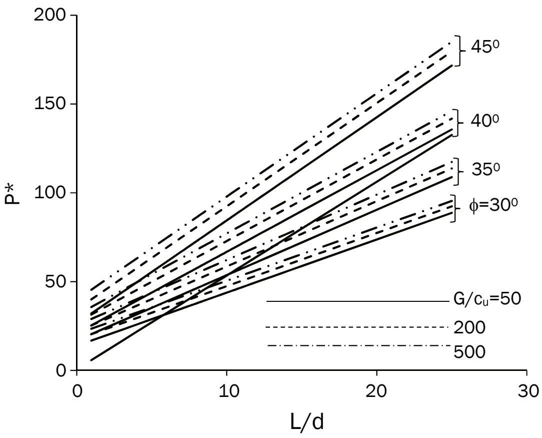

Fig. 6 Variation of Ultimate Pullout Capacity P* of GPA with L/d (Effect of G/c_u & ϕ_g for λ=1.3 & β = 1.0)

increasing from 30^0 to 45^0 for L/d=10 and G/c_u=200. Since P^* by pile failure is unaffected by ϕ_g, the transition from pile to bulging failure occurs at $(L/d)_{cr}$ values increasing with ϕ_g. The ultimate pullout capacities for bulging failure for $\phi_g \geq 40^0$ are greater than the corresponding values for pile failure. GPA thus functions just like a rigid solid pile in resisting uplift loads especially for ϕ_g greater than 35^0. Since the angle of shearing resistance of the granular material, ϕ_g, in GPA in most practical situations is greater than 35^0, GPA may be used with confidence in place of solid (RCC) piles.

The effect of the parameter, λ ($=\gamma_{gp}d/c_u$), signifying the relative unit weight of GPA with respect to the undrained strength of in situ soil, on the ultimate pullout capacity of the GPA is presented in Figure 7 for

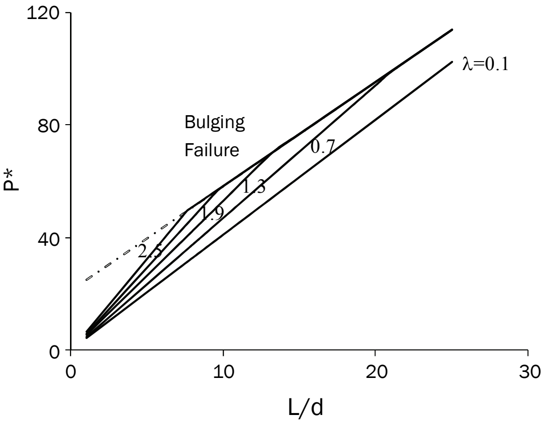

Fig. 7 Variation of P* vs. L/d (Effect of λ for β= 1, G/c_u=200 & ϕ=35^0)

β=1, G/c_u= 200 and ϕ=35^0. The parameter, λ, affects only the pile capacity and not the bulging capacity. The normalised capacity, P*, of GPA by pile failure increases linearly with L/d but is less than the capacity by bulging for λ=0.1. Small value of λ, e.g. λ=0.1, corresponds to very stiff soil whose bulging capacity could be significantly larger than the pile capacity. The rate of increase of P* with L/d, increases with increasing values of λ. P* values for L/d=10 increase from 38 for λ=0.1 to 45 and 56 for λ=0.7 and 1.3 respectively. Consequently, the transition from pile to bulging failure occurs at decreasing values of L/d for increasing values of λ. The transition from pile to bulging failure occurs at an L/d of about 7.5 for λ=2.5 and P* value of 52.

The variation of the ultimate capacity, P*, as a function of the lateral confining pressure co-efficient, β $[=\frac{\gamma_w.d}{c_u}(K_o.\alpha+1)]$, is studied in Figure 8 for λ=1.3, G/c_u=200 & φ=35^0. It should be noted that only the bulging capacity, P*, of GPA is affected by the parameter, β, and not the pile capacity. P* is nearly constant for low value of β (=0.1). The rate of increase of P* with L/d increases with β. The rate of increase of P* with L/d for λ=1.0 is only slightly less than that for pile failure. Values of P* for L/d=15 are 28, 45 and 82 for β equal to 0.1, 0.5 and 1.0 respectively. The transition from pile to bulging failure therefore occurs at increasing values of L/d for increasing values of β. Values of $(L/d)_{cr}$ are 5.2, 6.8 and 13.2 respectively for β values of 0.1, 0.5 and 1.0.

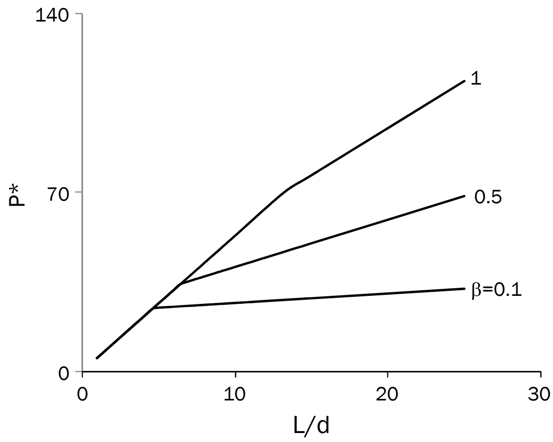

Fig. 8 Variation of P* vs. L/d (Effect of β for λ= 1.3, G/c_u=200 & ϕ=35^0)

The variations of $(L/d)_{cr}$ with G/c_u for β=1.0 and ϕ=35^0 and for different values of λ are presented in Figure 9. The critical length, $(L/d)_{cr}$ increases with increasing G/c_u. $(L/d)_{cr}$ increases from about 6 for G/c_u of 50 to about 8 for G/c_u of 500 for λ value of

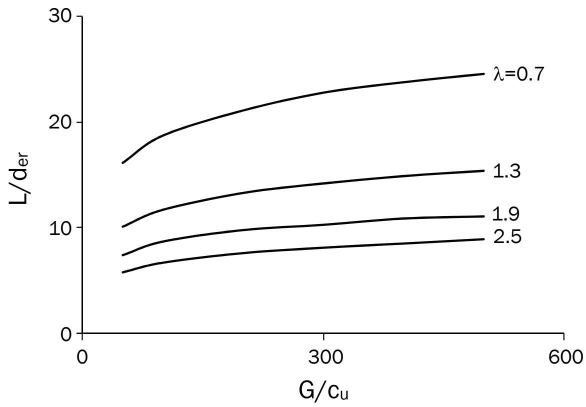

Fig. 9 Variation of $(L/d)_{cr}$ with G/c_u for GPA in Pullout (Effect of λ for β=1.0, & ϕ=35^0)

25 corresponding to dense granular pile material in soft ground. $(L/d)_{cr}$ increases with decrease of λ. Values of $(L/d)_{cr}$ for G/c_u of 50 and 500 corresponding to λ value of 0.7 are 16 and 24. $(L/d)_{cr}$ decreases from about 21 for $\lambda=0.7$ to about 7 for $\lambda=2.5$ for G/c_u value of 200. The variation of $(L/d)_{cr}$ with G/c_u is maximum at smaller values of $\lambda=0.7$. The rate of increase of $(L/d)_{cr}$ with G/c_u decreases with increase of λ becoming marginal for λ equal to 2.5.

Figure 10 plots the variation of $(L/d)_{cr}$ with G/c_u for $\lambda=1.3$ & $\phi=35^0$ and for increasing values of β. The critical length, $(L/d)_{cr}$ increases once again with increasing G/c_u for all values of β with the rate of increase with G/c_u increasing with increasing values of the parameter signifying the lateral confining earth pressure, β. $(L/d)_{cr}$ increases from 10 to 15 for G/c_u increasing from 50 to 500 for β value of 1.0. The corresponding values of $(L/d)_{cr}$ are 3.5 and 4.5 for β value of 0.1. The critical length, $(L/d)_{cr}$ increases from 4.2 to 13.1 for values of β increasing from 0.1 to 1.0 for G/c_u value of 200.

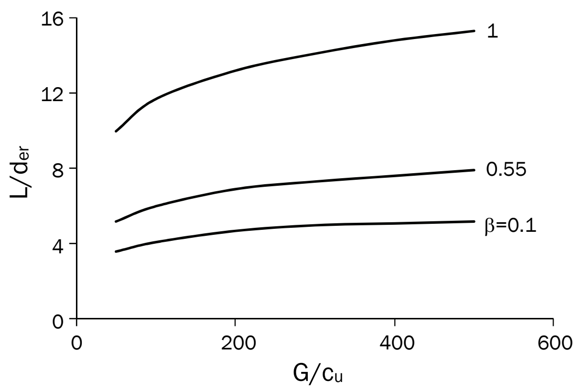

Fig. 10 Variation of $(L/d)_{cr}$ with G/c_u for GPA in Pullout (Effect of β for $\lambda=1.3$ & $\phi=35^0$)

Figure 11 plots the variation of the critical length with G/c_u for angles of shearing resistance of 30^0 and 35^0 for $\beta=1.0$ and $\lambda=1.3$. The critical length increases with increase in the angle of shearing resistance with

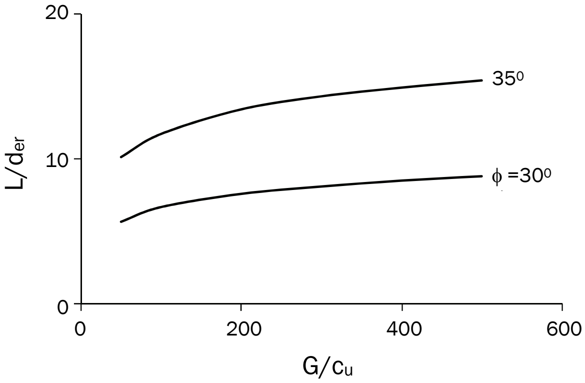

Fig. 11 Variation of $(L/d)_{cr}$ with G/c_u for GPA in Pullout (Effect of ϕ for $\lambda=1.3$ & $\beta=1.0$)

$(L/d)_{cr}$ increasing from 7 to 13 for ϕ increasing from 30^0 to 35^0 for G/c_u value of 200.

The GPA behaves more like a rigid/solid pile for smaller values of λ, higher values of β (higher lateral stress coefficients and soft ground) and higher angles of shearing resistance of GP material. Its performance is equivalent to that of relatively costlier rigid pile, if the granular pile material possesses high angle of shearing resistance of the order of 35 to 40^0. Use of well graded granular fill with proper compaction leading to high friction angle would make GPA preferable due to its low cost and ease of installation coupled with high performance.

Comparison of the Measured and Predicted Pullout Capacities

The ultimate pullout capacities predicted by the proposed theory are compared with those from the field test results of Lillis *et al.* (2004) who have presented two sets of in situ test results on pilot scale GPA for pullout. The GPA tested was of 0.61 m in diameter and 3.0 m long, with a channel section at the base fastened to two threaded rods serving as load transfer mechanism during uplift. The L/d ratio of the GPA tested was 4.92. The site is situated in a thick deposit of Connecticut Valley Varved Clay (CVVC). The soil profile (Figure 12) shows upper 2 m to consist of medium stiff clay with SPT values ranging from 10-19, below which, the soil is normally consolidated and with slightly

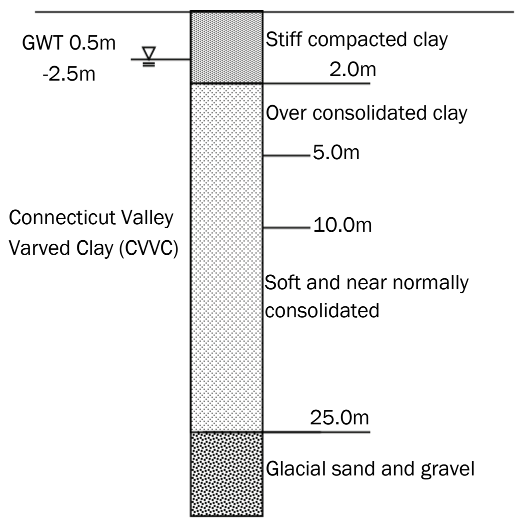

Fig. 12 Soil Profile of the National Geotechnical Experimentation Site (NGES)-Amherst

smaller SPT values up to a depth of 3 m (Figure 13). The soil is soft and near normally consolidated with SPT values reducing to 3 to 6 below 3 m depth. The water table showed a seasonal fluctuation between 0.5 m and 2.5 m below the ground level. The pullout force versus upward displacement for tests on GPA is presented in Figure 14.

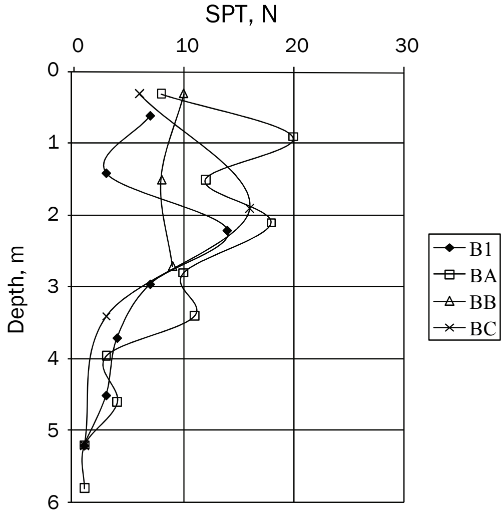

Fig. 13 SPT Data of the Site Conducted

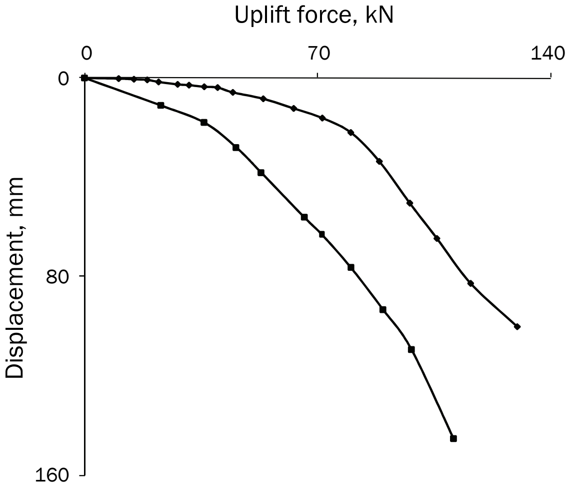

Fig. 14 Uplift Force vs. Tip Displacement of GPA (after Lillis *et al.* 2004)

The maximum pullout force, P*, to which the test was conducted is 130 kN resulting deflections of approximately 85 mm and 150 mm in tension rods respectively. However, the values estimated for the ultimate pullout loads from the rectangular hyperbola method are 169.5 kN and 196.0 kN. The N-values from SPT were used to estimate the average undrained strength of the in situ soil. The values of N are under considered under saturated condition as the depth of the water table is close to 0.5 m below the ground level. The values of N under saturated condition are presented in Table 1. The undrained modulus, E_s, and the shear modulus, G, were estimated from the initial slope of the load versus upward displacement plot and using the analysis of Madhav *et al.* (2005). The estimated ultimate loads are compared in Table 2 with the predicted ones corresponding to L/d = 4.92. The ratios of measured (or estimated ultimate capacities) with the predicted for first and second tests are 0.80 and 0.99, 0.93 and 1.14 for pile and bulging failure mechanism respectively. Thus the predicted ultimate capacities compare well with the measured (or estimated) values.

Table 1 Details of the GPA at Site and Values of N for Saturated State

D m	*L m*	*L/d*	*depth*	N_{dry}	N_{sat}	c_u *kPa*
0.61	3	4.92	1	7	4	18.75
			2	10	7	33.3
			3	12	9	50

Table 2 Comparison of Measured/Estimated (Lillis et al. 2004) and Predicted Ultimate Pullout Capacities

Test	*Angle of Shear Resistance, ϕ deg*	*Average c_u kPa*	$P_{ult,Pile}$ *kN*	c_u *at (L-d/2) kPa*	G/c_u	N_φ	N_c	σ_{ho} *kPa*	$P_{ult,bulg}$ *kN*	$P_{ult,est}$ *kN*	P_{ult} *meas/*P_{ult} *pre - Pile*	P_{ult} *meas/*P_{ult} *pre - Bulging*
1	30	34	211.0	33.3	50	3.0	4.91	32.34	171.8	169.5	0.80	0.99
2	30	34	211.0	33.3	50	3.0	4.91	32.34	171.8	196.0	0.93	1.14

Conclusions

The Granular Pile Anchor (GPA) is a relatively new concept that extends the functional utility of granular piles to withstand pullout or tensile loads. A method for the estimation of the ultimate pullout capacity of GPA is been presented considering the in situ soil conditions to be homogenous. A parametric study quantifies the values for the ultimate pullout capacity and the critical length of GPA for different values of L/d and G/c_u ratios, K_0 and ϕ_g. The pullout capacity and the critical length of the GPA increase with increasing values of all the above parameters. Consequently, the failure of GPA due to pile failure mechanism extends on to longer lengths and becomes identical to that of rigid piles. The GPA, thus, is as effective in resisting pullout forces as a rigid pile and can be cost effective compared to rigid RCC or steel piles. The proposed theory is validated with the measured pullout test data from Lillis *et al.* (2004).

List of Symbols

c_u	Undrained strength of in situ soil
d	Diameter of GPA
G	Shear Modulus of in situ soil
K_0	Coefficient of lateral stress a rest
L	Length of GPA
L_{cr}	Critical length of GPA
N^*_c	Bearing capacity factor
P_{ult}	Ultimate pullout capacity of GPA
P^*	Normalised pullout capacity of GPA
γ_{gp}	Unit weight of granular pile material
γ_s	Saturated unit weight of in situ soil
γ_{sub}	Submerged or buoyant unit weight of in situ soil
ϕ_g	Angle of shearing resistance of granular pile material
β	Lateral earth pressure co-efficient
λ	Relative density of the pile material
α	Ratio of submerged unit weight of soil to unit weight of water

References

Aboshi, H. & Suemastu, N. (1985): 'The Sand Compaction Pile Method: State-of-The-Art-Paper' Proc. 3rd Int. Geotech. *Seminar on Soil Improvement Methods*, Nanyang Technological Institution, Singapore.

Aboshi, H., Icimoto, E., Enoki, M & Harda, K. (1979): 'The Composer- A Method to Improve Characteristics of Soft Clays by Inclusion of Large Diameter Sand Columns' *Proc. Int. Conf. on Soil Reinforcement: Reinforced Earth and Other Techniques*, Paris, Vol.1, pp211-216.

Barksdale, R.D. & Bachus, R.C. (1983): 'Design and Construction of Stone Columns' *Report No. FHWA/RD-83/026*, National Information Service, Springfield, Virginia, U.S.A.

Baumann, V. & Bauer, G.E.A. (1974): 'The Performance of Foundation on Various Soils Stabilized by Vibro-Compaction Method' *Canadian Goetech. Journal,* Vol.11, pp509-530.

Engelhardt, K. & Kirsch K. (1977): 'Soil Improvement by Deep Vibratory Techniques' *Proceedings of 5th South East Asian Conf. on soil Mech. and Found. Eng.*, Bangkok.

Gibson, R.E. & Anderson, W.F. (1961): 'In-Situ Measurement of Soil Properties with the Pressuremeter' *Civ. Engrg. & Publ. Works Rev.*, Vol.56, No.658.

Hughes, J.M.O. & Withers, N.J. (1974): 'Reinforcing Soft Cohesive Soil with Stone Columns' *Ground Engineering*, Vol.7 (3), 42-49.

Hughes, J.M.O., Withers, N.J. & Greenwood, D.A (1975): 'A Field Trial of the Reinforced Effect of Stone Column in Soil' *Geotechnique,* Vol. 25, No.1, 31-44.

Kumar, P., Ranjan, G. & Saran, S. (2003): 'GAP System for Resistance of Uplift Forces –A Field Study' *Proceedings of IGC,* pp597-602.

Lawton, E.C., Fox, N.S. & Handy, R.L. (1994): 'Control of settlement and uplift of structures using short aggregate piers' *In-situ Deep Soil Improvement, Proc. ASCE National Convention, Atlanta, Georgia,* pp121-132.

Lillis, C., Lutenegger, A.J & Adams, M. (2004): 'Compression and Uplift of Rammed Aggregate Piers in Clay' *Geosupport*: ASCE/GEO Geotechnical Special Publication no. 14, 497-507.

Madhav, M. R. & Arlekar, J.N. (2000): 'Dilation of Granular piles in mitigating Liquefaction of sand deposit' *Proc. of 12th World Conference on Earthquake Engineering, Auckland, New Zealand*.

Madhav, M.R., Vidyaranya, B. & Sivakumar, V. (2005): 'Ultimate Pullout Resistance and Displacements under Working Loads of GPA' Keynote Lecture, IGC 2005, *Ahmadabad,* pp 45-52.

Mitchell, J.K. & Wentz, F.J. (1991): 'Performance of improved ground during the Loma Preita earthquake' *UCB/EERC report 91/92*.

Ohbayashi, J., Harda, K. & Yamamoto, M. (1999): 'Resistance against Liquefaction of Ground Improved by Sand Compaction Pile Method' *Earthquake Geotechnical Engrg., ed. by Seco a Pinto*, *Balkema, Rotterdam,* pp. 312.

Phanikumar, B.R. & Rao, N.R. (2000): 'Increasing Pullout Capacity of Granular Pile Anchors using Base Geosynthetics' *Canadian Geotechnical Journal,* Vol.37, 870-881.

Phanikumar, B.R., Sharma, R.S., Srirama Rao, A. & Madhav, M.R. (2004): 'Granular Pile Anchor Foundation (GPAF) System for Improving the Engineering Behaviour of Expansive Clay Beds' *Geotechnical Testing Journal, American Standard Testing Machines,* Vol.27(3), 1-9.

Ranjan, G. & Kumar, P. (2000): 'Behaviour of Granular Piles under Compressive and Tensile Loads' *Geotechnical Engineering, Journal, of SEAGS,* Vol.31, (3), 209.

Sabhahit, N., Basudhar, P.K. & Madhav, M.R. (1997): 'Generalised Stability Analysis of Embankments on Granular Piles, Soils and Foundations' Vol.37, (4), 13-22.

Seed, H.B., & Booker, J.R., (1977): 'Stabilization of potentially liquefaction sand deposit using gravel drains' Journals of the Geotechnical Engineering *Division, ASCE,* 103(GT7), 757-768.

Seed, H.B., Martin, P.P & Lysmer, J. (1976): 'Pore water pressure changes during soil liquefaction' *Journal of the Geotechnical Engineering Division, ASCE,* 102(GT4), 323-346.

Setty Narayanaswamy, K.R., Ravi Shanker, A.U. & Narasimha Reddy, G.N. (2000): 'Uplift Behaviour of Granular Pile-Anchors in Expansive Soils' *Indian Geotechnical Conference, IIT Bombay,* pp.305-306.

Sharma, R.S. & Phanikumar, B.R. (2005): 'Laboratory Study of Heave Behaviour of Expansive Clay Reinforced with Geopiles' *Journal of Geotechnical & Geoenvironmental Engineering, ASCE,* Vol. 131, (4). 512-520.

White, D., Wissmanm, K., & Lawton, E. (2001): 'Geopier Reinforcement for Transportation Application' *Geotechnical News,* pp. 63-68.

Wissmann, K.J. & N.S. Fox, N.S. (2000a): 'Design and Analysis of Short Aggregate Piers Used to Reinforce Soils for Foundation Support' *Proceedings, Geotechnical Colloquium. Technical University Darmstadt. Darmstadt, Germany,* March.

Wissmann, K.J., Fox, N.S. &Martin, J.P. (2000b): 'Rammed Aggregate Piers Defeat 75-foot Long Driven Piles' Performance Confirmation of Constructed Geotechnical Facilities, ACSE Geotechnical Special Publication No. 94, April 9-12. Amherst Massachusetts.