Article:

Zhuang, P orcid.org/0000-0002-7377-7297 and Yu, HS orcid.org/0000-0003-3330-1531 (2018) Uplift resistance of horizontal strip anchors in sand: a cavity expansion approach. Géotechnique Letters, 8 (4). pp. 1-18. ISSN 2045-2543

https://doi.org/10.1680/jgele.18.00083

Uplift resistance of horizontal strip anchors in sand: a cavity expansion approach

Pei-Zhi Zhuang, Research fellow

Corresponding author, Email: P.zhuang@leeds.a.cuk

Hai-Sui Yu, Professor and Deputy Vice-Chancellor

Email: H.Yu@leeds.ac.uk

School of Civil Engineering, Faculty of Engineering,

University of Leeds, LS2 9JT Leeds, UK

Abstract: This letter presents an analytical cavity expansion theory-based method for predicting peak uplift resistance of shallow horizontal strip anchors buried in sand. Based on an analytical two-dimensional stress solution for loading analysis around a cylindrical cavity, the method was developed by assuming that the peak anchor uplift resistance can be approximated by the cavity breakout pressure. In the new cavity expansion model, the ultimate failure is reached once the plastic zone develops to the ground surface, and the biaxial state of in-situ ground stresses is taken into account. A database consisting of 75 model tests on shallow strip anchors in sands was compiled to valid the new method. The predicted results and measured data are in reasonable agreement, with a mean over-prediction of the peak uplift resistance by 1.6%. The reliability of the new solution was also checked by comparing with other commonly used analytical solutions. It is shown that the present solution can provide a simple analytical tool for predictions of the peak uplift resistance of strip anchors in sand while a sliding-block failure mechanism dominates.

Keywords: Anchors & anchorages, Bearing capacity, Sands

INTRODUCTION

Horizontal plate anchors are commonly used for resisting uplift forces in many engineering structures such as transmission towers, drydocks, mooring systems for ocean surface or submerged platforms. As a principal tool in the routine design of earth anchors, a number of analytical solutions for predicting the uplift resistance have been proposed based on theoretical approaches such as limit equilibrium (Meyerhof and Adams, 1968, White et al., 2008), limit analysis (Murray and Geddes, 1987), and cavity expansion theory (CET) (Vesic, 1971, Yu, 2000). Among them, solutions based on the former two approaches have been developed fairly well over decades, but, by contrast, solutions based on cavity expansion theory received limited attention. It is necessary to further check and improve the accuracy and the applicability of the CET-based solutions, especially for applications to shallow plate anchors in sand as discussed later. A comprehensive overview of earth anchors refers to Das and Shukla (2013).

In the cavity expansion approach, the breakout pressure of an internally pressurized cavity is often used to predict the uplift capacity of a single horizontal plate anchor. Previous CET-based models mainly include Vesic's method (1971) and Yu's method (2000). The failure criteria used to determine the peak resistance in these two methods both have been expressed by a relationship between the relative radius of the elastic-plastic boundary in the loading analysis around a cavity and the soil cover depth above the anchor. In Vesic's method, the propagation of the plastic zone was determined through a quasi-static expansion analysis considering soil compressibility. In Yu's method, the radius of the elastic-plastic boundary was directly expressed by the soil cover depth multiplying an empirical coefficient m. It has been demonstrated that, taking the moment at which the plastic zone just reaches the ground surface as the ultimate failure criterion (i.e. $m = 1$), Yu's method can give fairly accurate predictions of the maximum uplift resistance of shallow anchors in undrained clays (Chen et al., 2013, Merifield et al., 2001, Yu, 2000). Nevertheless, the accuracy of previous CET-based methods is not that generally satisfactory for applications to plate anchors in sand. For example, although the Vesic's method may perform well for uplift resistance predictions of shallow plate anchors in loose sand, a considerable underprediction would be made while applied to anchors in dense sand (Das and Shukla, 2013, Murray and Geddes, 1987). In Yu's method, an approximate value around 0.5 of the introduced coefficient m was suggested for anchors in sand to match the results computed from upper bound limit analyses. However, theoretical methods for determining the value of m have not been obtained till now.

In both Vesic's (1971) and Yu's (2000) models, the adopted cavity expansion solutions had been derived with the idealisation that the internal and far-field stresses are uniform (Vesic, 1972, Yu and Houlsby, 1991). However, in-situ horizontal and vertical soil stresses usually are not equal (i.e. the earth pressure coefficient at rest K_0 is not ideally equal to unity) (Guo, 2010, Lee et al., 2013, Mayne and Kulhawy, 1982). Rowe and Davis (1982a, 1982b) pointed out that the load-deformation characteristics of soil around a plate anchor depend on the value of K_0. Likewise, under biaxial far-field stresses, the plastic zone developed around a cylindrical cavity may significantly differ from that computed by a simplified one-dimensional analysis (Bradford and Durban, 1998, Detournay, 1985, 1986, Galin, 1946, Zhuang and Yu, 2018). It was introduced above that the criteria used to determine the anchor uplift capacity in the CET-based models are associated with the propagation of the plastic zone and its relative position to the ground surface. For these reasons, it is believed that the possible K_0 effect should be taken into account in the cavity expansion approach for anchor uplift capacity predictions.

In the light of above discussions, an analytical CET-based solution is developed to predict the uplift resistance of horizontal strip anchors in sand by additionally considering biaxial in-situ stresses in the stress analysis around a cylindrical cavity under loading. The new solution is validated by comparing with 75 pull-out model tests with strip plate anchors performed in sand and other commonly used analytical models.

CAVITY EXPANSION APPROACH FOR ANCHOR UPLIFT CAPACITY PREDICTION

For a horizontal strip plate anchor pulling-out at a sufficiently slow rate, the peak uplift resistance experienced is assumed to equal the sum of the ultimate radial pressure (p_u) needed to break out a cylindrical cavity underneath the ground surface and the weight of the soil occupied by the volume of a half cavity above the plate anchor (W_s) as depicted in Fig. 1 (Vesic, 1971). For a plate anchor placed at relatively shallow depths, it has been suggested by Vesic (1971) and Yu (2000) that the breakout of a plate anchor occurs while the outer boundary of the plastic zone predicted by a cavity expansion analysis is sufficiently close to or at the ground surface. While elastic-perfectly-plastic cavity expansion solutions derived under hydrostatic stress conditions are applied, Yu (2000) demonstrated that an empirical coefficient m has to be introduced to relate the maximum radius of the plastic region ($r_{ep}\big|_{max}$) and the soil cover depth above the anchor, that is $r_{ep}\big|_{max} = mH$. Accordingly, based on a stress analysis around a cylindrical cavity adopting the Mohr-Coulomb yield criterion (Yu, 2000), p_u for an anchor in cohesionless materials can be expressed as:

$$p_u = p_0 F_q = p_0 \frac{2K_p}{K_p + 1}\left(2m\frac{H}{D}\right)^{(1-1/K_p)} \tag{1}$$

where p_0 is the effective soil stress above the anchor, namely $p_0 = \gamma' H$. γ' is the effective unit weight of the soil. H is the embedment depth of a plate anchor. D is the anchor breadth. $K_p = (1+\sin\varphi)/(1-\sin\varphi)$. φ represents the effective friction angle of soil.

Then the dimensionless anchor breakout factor in cohesionless materials equals:

$$N_{\gamma-sand} = \frac{p_u D + W_s}{\gamma' HD} = F_q + \frac{\pi}{8}\frac{D}{H} \tag{2}$$

By definition, the value of m is influenced by the boundary conditions and load-deformation characteristics of soil above the plate anchor. In reality, the coefficient of earth pressure at rest in sands normally is less than unity (Guo, 2010, Mayne and Kulhawy, 1982). To additionally account for the K_0 effect in the loading analysis around a cylindrical cavity, the asymptotic mapping function of equation (A- 1) in the appendix is used to estimate the distribution of the plastic zone (Detournay, 1985, Zhuang and Yu, 2018). It gives that the range of the plastic zone in the vertical direction is $[\lambda(1-\beta)^{(1-\delta)}]$ times of that predicted by the corresponding solution derived under equivalent uniform initial stresses. Thus, with the same assumption that the peak uplift resistance is reached once the plastic zone propagates to the free ground surface, an approximate theoretical expression of the coefficient m in equation (1) can be derived as:

$$m = \frac{1}{\lambda(1-\beta)^{1-\delta}} \tag{3}$$

in which

$$\lambda^{1-1/K_p} = {}_2F_1[(-\delta,-\delta);1;\beta^2] = 1 + \delta^2\beta^2 + 0(\beta^4) \tag{4}$$

where $\delta=(1-K_p)/(1+K_p)$; $\beta=\tau_\infty/S_p$. $P_\infty=-(\sigma_{v0}+\sigma_{h0})/2$; $\tau_\infty=(\sigma_{h0}-\sigma_{v0})/2$, $S_p=[(1-K_p)P_\infty]/(K_p+1)$; $\sigma_{v0}=\gamma' H$. $\sigma_{h0}=K_0\sigma_{v0}$. ${}_2F_1[(a,b);c;z]=\sum_{n=0}^{\infty}\frac{(a)_n(b)_n}{(c)_n}\frac{z^n}{n!}$ ($|z|<1$) is a Gaussian or ordinary hypergeometric function. K_0 is approximated by the commonly used Jaky's (1948) equation here, namely $K_0=1-\sin\varphi_{crit}$. φ_{crit} represents the critical state friction angle of sand. Note that $\beta=0$ and $m=1$ while K_0 equals unity.

For a strip plate anchor placed in sand, the uplift response mainly varies with the relative embedment depth (H/D) and sand relative density (D_r) (Ilamparuthi et al., 2002, Liu et al., 2011, Merifield and Sloan, 2006). At relatively shallow depths, a sliding-block failure mechanism (global shear failure) dominates. The peak uplift resistance is mobilised while a pair of distributed shear zones stemming from the edges of the anchor extend to the ground surface (e.g. Fig. 1) and increases proportionally with increases of H/D. At greater depths, the uplift resistance is primarily determined by the localized compression (local shear failure) and the failure plane may not develop to the ground surface. The transition depth between the global shear failure mode and the local shear failure mechanism varies with state and deformation characteristics of the soil above (Chen et al., 2013, Meyerhof and Adams, 1968). As it assumes that the ultimate failure occurs while the plastic zone develops to the ground surface, the present solution (i.e. equations (2) and (3)) is designed for shallow strip anchors pulled out to failure with a sliding-block mechanism.

The mobilised friction angle φ can be measured in tests under similar sand state and stress level of sand above the plate anchor at failure. Alternatively, the Bolton's (1986, 1987) empirical equation (i.e. Eq.(5)) is employed to estimate φ which might be stress- and state-dependent (Bradshaw et al., 2016). In conjunction with the Bolton's correlation, the present solution can be recast in terms of φ_{crit} , D_r , p'_m , and H/D that can be easily determined during a site investigation.

$$\varphi_{peak}-\varphi_{crit}=A_\psi I_R \tag{5}$$

where I_R is a dilation indicator, spanning the range of 0 to 4. $I_R=D_r(Q-\ln p'_m)-1$ while $p'_m\geq 150\text{kPa}$ (Bolton, 1986); $I_R=5D_r-1$ while $p'_m<150\text{kPa}$ (Bolton, 1987). A_ψ is taken as 5 for the strip anchor uplift problem (plane strain). Q is the natural logarithm of the grain crushing strength (in kPa) (Randolph et al., 2004), which is sand-specific and stress-level dependent (Chakraborty and Salgado, 2010). Typical values of Q and φ_{crit} for a variety of sands have been summarized by Randolph et al. (2004). p'_m is the mean confining stress at failure, kPa. For simplicity, it is taken as the effective overburden soil pressure at the depth of H here, that $p'_m = \gamma' H$ (White et al., 2008).

COMPARISON WITH MODEL TEST RESULTS AND DISCUSSION

In order to assess the new solution thoroughly, a database comprising 75 pull-out tests on model plate anchors in sands has been assembled. To simulate the plane strain condition, only tests on plate anchors with an aspect ratio of L/D (length/breadth) greater than 7 have been included as suggested in results reported by Murray and Geddes (1987) and Rowe and Davis (1982b). To roughly meet the requirement of the sliding-block failure mechanism, only tests with an embedment ratio of $H/D \leq 8$ (White et al., 2008) are collected. The database spans a wide range of relative density (D_r=17~86%, mean 37.8%) and embedment depths (H/D=1~8, mean 4.35). Details of each test series are summarised in Table 1.

Taking the measured parameters given in Table 1, anchor breakout factors of the test database have been back-calculated using equations (2) and (3), and they are compared with the test data in

Fig. 2, plotted against relative density and embedment ratio. It is shown that a mean over-prediction of the peak uplift resistance by 1.6% is made by the new solution, and the coefficient of variation (COV) is 0.15. Relatively significant outliners (overpredictions) appear in tests of Dickin (1988) with loose sand at relatively deep depths as marked in the graphs. As reasonable predictions are shown for tests of Dickin (1988) that were performed in dense sand at H/D=1-8 and in loose sand at H/D=1-4, it is believed that the overpredictions are because a local failure mechanism dominates in loose sand at H/D>4 rather than the sliding-block failure mechanism associated with the current method (Meyerhof and Adams, 1968).

Alternatively, φ in the new solution may be approximated by the peak plane-strain friction angle calculated using equation (5) (i.e. $\varphi = \varphi_{\mathrm{peak}}$). As the tests of this database are all performed in silica sands, Q in equation (5) is taken as 10 (Bolton, 1986). All other input parameters are taken from the sources references as summarised in Table 1 without any optimisation. Fig. 3 shows that the calculated results by the alternative method also compare favourably with the test results of the database.

It has been stated that the propagation of the plastic zone is influenced by the boundary conditions and soil deformation above the plate anchor. Experimental investigations (Ilamparuthi et al., 2002, Liu et al., 2011, Merifield and Sloan, 2006, White et al., 2008) showed that increasing dilation may occur above the anchor at failure in denser sand which accompanied by more lateral volume expansions. As a result, extra lateral confining pressure would be mobilised. This can be confirmed by back-calculating the far-field earth pressure coefficient using equations (1) and (3). In the present solution, the earth pressure coefficient is conservatively taken as the in-situ value for simplicity. As sand dilation is strong state-dependent (Bolton, 1986, Li and Dafalias, 2000), both stress level and initial density could affect the value of m. Values of the coefficient m defined in equation (1) have been back-calculated with the measured anchor factors and are plotted in Fig. 4. In the present database of tests, the dependency of m on the sand relative density is more significant, and a linear relationship between m and $\mathrm{D_r}$ was fitted in Fig. 4. Meanwhile, example results calculated using equations (3) and (5) are also plotted, taking $\mathrm{p'_m} = 40\mathrm{kPa}$, $\mathrm{H/D} = 5$ for illustration purpose. The theoretical solution predicts that m increases with relative density and earth pressure coefficient. Although the mobilised lateral confining pressure might be slightly greater than that at rest, the back-calculated m of this database mostly distribute in the range calculated by equation (3) incorporating the Bolton's equation (i.e. equation (5)) with typical in-situ values of $\mathrm{K_0}$.

COMPARISON WITH ANALYTICAL METHODS

The new solution is also compared with the commonly used limit equilibrium methods and upper-bound plasticity solution in Fig. 5. In these methods, the break-out factor of strip plate anchors in sand can be expressed in a unified form of

$$\mathrm{N}_{\gamma-\mathrm{anchor}} = 1 + \mathrm{f_{up}} \frac{\mathrm{H}}{\mathrm{D}} \tag{6}$$

where

$$\mathrm{f_{up-1}} = \tan\psi + (\tan\varphi_{\mathrm{peak}} - \tan\psi)\left[\frac{1+\mathrm{K_0}}{2} - \frac{(1-\mathrm{K_0})\cos 2\psi}{2}\right] \quad \text{(White et al., 2008) (6 a)}$$

$$\mathrm{f_{up-2}} = \mathrm{K_u} \tan\varphi \quad \text{(Meyerhof and Adams, 1968) (6 b)}$$

$$f_{up-3} = \tan\varphi \qquad \text{(Murray and Geddes, 1987) (6 c)}$$

By assuming that the inclination angle of shear planes (ω) on each side of the inverted trapezoidal block equals the angle of dilation (ψ) (i.e. $\omega = \psi$ in Fig. 1), a simple limit equilibrium solution as Eq.(6 a) was derived by White et al. (2008). Eq.(6 b) gives the limit equilibrium solution of Meyerhof and Adams (1968). K_u was suggested equal 0.95 for strip anchors. Equation (6 c) is the upper-bound plasticity solution (Murray and Geddes, 1987), in which the normality is satisfied (i.e. $\omega = \varphi$ in Fig. 1).

It has been reported that the upper-bound solution can give reasonable predictions of the uplift resistance of strip anchors (Merifield and Sloan, 2006) but may be unconservative for materials obeying a non-associated flow rule (Murray and Geddes, 1987). With the same inputs of sand properties, Fig. 5 (a) shows that the proposed method gives slightly lower predictions than the upper-bound plasticity solution. Meanwhile, it is shown in Fig. 5 (a) that much higher values are predicted by the new CET-based solution than those by Vesic's (1971) solution in dense sand while similar results in loose sand. By using the Bolton's correlation, Fig. 5 (b) shows that the anchor break-out factors predicted by this method are generally higher than those by the limit equilibrium solution of White et al. (2008). White et al. (2008) also reported that their solution underpredicted the results of model tests on strip plate anchors by 14%. In addition, White et al. (2008) showed that their method overpredicted the results of model pipes with relatively smooth pipe surfaces by 11%. As the interface frictional behaviour is expected to be more significant for a pipe than a horizontal anchor, overpredictions are to be expected if the present solution was to be used for pipes with smooth surfaces. Overall, the above comparisons encouragingly suggested that the new CET-based solution can provide a simple and reliable analytical method for the peak uplift resistance predictions of strip anchors in addition to other commonly used methods.

CONCLUSIONS

By additionally considering the biaxial state of in-situ ground stresses in the loading analysis of a cylindrical cavity, a new theoretical method was developed for predicting the uplift resistance of strip plate anchors in sand. A database of 75 model tests on strip anchors in sands has been assembled to validate the new method. Good agreement was shown between the predicted and measured results, with a mean over-prediction of the peak uplift resistance by 1.6%. Although the level of agreement may vary with the scope of the database, these encouraging agreements suggested that the peak uplift resistance of strip anchors that determined by a sliding-block mechanism can be well predicted by the new analytical CET-based method. And the accuracy and applicability of the new method were further demonstrated by comparing with other representative plasticity solutions and limit equilibrium solutions.

APPENDIX: Plastic failure zone under biaxial in-situ ground stresses

Under biaxial far-field stresses, the non-circular elastic-plastic boundary developed around an internally pressurised cylindrical cavity surround by Mohr-Coulomb materials can be described by the asymptotic mapping function in equation (A-1) (Detournay, 1985, Zhuang and Yu, 2018) while the plastic zone is statically determinate.

$$\omega(\sigma) = \alpha\sigma(1+\frac{\beta}{\sigma^2})^{(1-\delta)} \qquad \text{(A- 1)}$$

where $\omega(\sigma)$ conformally maps the elastic-plastic boundary in the physical plane to the unit circle in the phase plane (Muskhelishvili, 1963). $\alpha = \lambda\chi \mathrm{R}$. $\mathrm{R} = \mathrm{D}/2$. $\sigma = \mathrm{e}^{\mathrm{i}\phi}$. ϕ is an argument of the complex variable σ. $\mathrm{i} = \sqrt{-1}$. $\chi = \left\{ \frac{(1+1/\mathrm{K_p})}{2} \frac{[(\mathrm{K_p}-1)\,\mathrm{p_u}]}{[(1-\mathrm{K_p})\mathrm{P_\infty}]} \right\}^{\mathrm{K_p}/(\mathrm{K_p}-1)}$. Note that equation (A-1) is obtained from the loading analysis of a cylindrical cavity in an infinite medium. Consequently, the free ground surface effect is not taken into account in the present approximate CET-based model.

REFERENCES

Bolton, M. D. (1986). The strength and dilatancy of sands. Géotechnique **36**, No. 1, 65-78.

Bolton, M. D. (1987). Discussion on the strength and dilatancy of sands. Géotechnique **37**, No. 2, 219-226.

Bradford, I. D. R. & Durban, D. (1998). Stress and deformation fields around a cylindrical cavity embedded in a pressure-sensitive elastoplastic medium. Journal of Applied Mechanics **65**, No. 2, 374-379.

Bradshaw, A., Giampa, J., Gerkus, H., Jalilvand, S., Fanning, J., Nanda, S., Gilbert, R., Gavin, K. & Sivakumar, V. (2016). Scaling Considerations for 1-g Model Horizontal Plate Anchor Tests in Sand. Geotechnical Testing Journal **39**, No. 6, 1006-1014.

Chakraborty, T. & Salgado, R. (2010). Dilatancy and shear strength of sand at low confining pressures. Journal of Geotechnical and Geoenvironmental Engineering **136**, No. 3, 527-532.

Chen, Z., Tho, K. K., Leung, C. F. & Chow, Y. K. (2013). Influence of overburden pressure and soil rigidity on uplift behavior of square plate anchor in uniform clay. Computers and Geotechnics **52**, 71-81.

Das, B. M. & Shukla, S. K. (2013). Earth anchors. 2nd edn. USA: J. Ross Publishing.

Detournay, E. (1985). Solution approximative de la zone plastique autour d'une galerie souterraine soumise a un champ de contrainte non hydrostatique. In Comptes Rendus-Academie des Sciences Serie II. vol. 301 (12), pp. 857-860 (in French).

Detournay, E. (1986). An approximate statical solution of the elastoplastic interface for the problem of Galin with a cohesive-frictional material. International Journal of Solids and Structures **22**, No. 12, 1435-1454.

Dickin, E. A. (1988). Uplift behavior of horizontal anchor plates in sand. Journal of Geotechnical Engineering **114**, No. 11, 1300-1317.

Dickin E. A. 1994. Uplift Resistance of Buried Pipelines in Sand. Soils and Foundations **34**, No. 2, 41-48.

Dickin, E. A. & Laman, M. (2007). Uplift response of strip anchors in cohesionless soil. Advances in Engineering Software **38**, No. 8, 618-625.

Galin, L. A. (1946). Plane elastic-plastic problem: plastic regions around circular holes in plates and beams. Prikladnaia Matematika i Mekhanika **10**, 365-386.

Guo, P. (2010). Effect of density and compressibility on K_0 of cohesionless soils. Acta Geotechnica **5**, No. 4, 225-238.

Ilamparuthi, K., Dickin, E. & Muthukrisnaiah, K. (2002). Experimental investigation of the uplift behaviour of circular plate anchors embedded in sand. Canadian Geotechnical Journal **39**, No. 3, 648-664.

Jaky, J. (1948). Pressure in silos. In Proceedings of the 2nd International Conference on Soil Mechanics and Foundation Engineering. Rotterdam, vol. 1, pp. 103-107.

Lee, J., Yun, T. S., Lee, D. & Lee, J. (2013). Assessment of K_0 correlation to strength for granular materials. Soils and Foundations **53**, No. 4, 584-595.

Li, X.S. & Dafalias, Y. F. (2000). Dilatancy for cohesionless soils. Géotechnique **50**, No. 4, 449-460.

Liu, J., Hu, H. & Yu, L. (2013). Experimental study on the pull-out performance of strip plate anchors in sand. In Proceedings of the Twenty-third International Offshore and Polar Engineering Anchorage. Alaska, USA, pp. 616-623.

Liu, J., Liu, M. & Zhu, Z. (2011). Sand deformation around an uplift plate anchor. Journal of Geotechnical and Geoenvironmental Engineering **138**, No. 6, 728-737.

Mayne, P. W. & Kulhawy, F. H. (1982). K_0- OCR Relationships in Soil. Journal of the Soil Mechanics and Foundations Division **108**, No. 6,851-872.

Merifield, R., Sloan, S. & Yu, H. (2001). Stability of plate anchors in undrained clay. Géotechnique **51**, No. 2, 141-154.

Merifield, R. S. & Sloan, S. W. (2006). The ultimate pullout capacity of anchors in frictional soils. Canadian Geotechnical Journal **43**, No. 8, 852-868.

Meyerhof, G. G. & Adams, J. I. (1968). The ultimate uplift capacity of foundations. Canadian Geotechnical Journal **5**, No. 4, 225-244.

Murray, E. J. & Geddes, J. D. (1987). Uplift of anchor plates in sand. Journal of Geotechnical Engineering **113**, No. 3, 202-215.

Muskhelishvili, N. I. (1963). Some basic problems of the mathematical theory of elasticity. 4th edn. Groningen, the Netherlands.: P. Noordhoff.

Randolph, M. F., Jamiolkowski, M. B. & Zdravkovic, L. (2004). Load carrying capacity of foundations. In Advances in Geotechnical Engineering: The Skempton Conference. London, vol. 1, pp. 207-240.

Ravichandran, P. T. & Ilamparuthi, K. (2008). Uplift Behaviour of Strip Anchor in Sand and Reinforced Sand Beds. Indian Geotechnical Journal **38**, No. 2, 156-170.

Rowe, R. K. & Davis, E. H. (1982a). The behaviour of anchor plates in clay. Géotechnique **32**, No. 1, 9-23.

Rowe, R. K. & Davis, E. H. (1982b). The behaviour of anchor plates in sand. Géotechnique **32**, No. 1, 25-41.

Vesic, A. S. (1971). Breakout resistance of objects embedded in ocean bottom. Journal of the Soil Mechanics and Foundations Division **97**, No. 9, 1183-1205.

Vesic, A. S. (1972). Expansion of cavities in infinite soil mass. Journal of Soil Mechanics and Foundations Division **98**, No. SM3, 265-290.

White, D. J., Cheuk, C. Y. & Bolton, M. D. (2008). The uplift resistance of pipes and plate anchors buried in sand. Geotechnique **58**, No. 10,771-779.

Yu, H. S. (2000). Cavity expansion methods in geomechanics. The Netherlands: Kluwer Academic Publishers.

Yu, H. S. & Houlsby, G. T. (1991). Finite cavity expansion in dilatant soils: loading analysis. Géotechnique **41**, No. 2, 173-183.

Zhuang, P. Z. & Yu, H. S. (2018). A unified analytical solution for elastic-plastic stress analysis of a cylindrical cavity in Mohr-Coulomb materials under biaxial in-situ stresses. Géotechnique, https://doi.org/10.1680/jgeot.17.P.281.

Table

Table 1 Model test database of horizontal strip anchor uplift resistance

Authors	Sand	Number of tests	Aspect ratio (L/D)	Cover depth Ratio(H/D)	Relative density (%)	Sand friction angle	
						φ (°)	φ_{crit} (°)
Rowe and Davis (1982b)	Sydney sand	36	8.75	1-8	17-37	32-33.3	31
Murray and Geddes (1987)	Medium grained sand	4	10	1-6	85.9	44	32
Dickin (1988) [*]	Erith sand	15	8	1-8	33-76	38-49	35[†]
Ravichandran and Ilamparuthi (2008)	Palar river sand	9	7	2-4	34-85	33-43	31
Liu et al. (2013)	Fujian standard sand	11	plane strain	1-7	30-80	34-43	31

[*] Centrifuge test at 40g, all other tests at 1g. [†] Dickin and Laman (2007).

List of figures and table

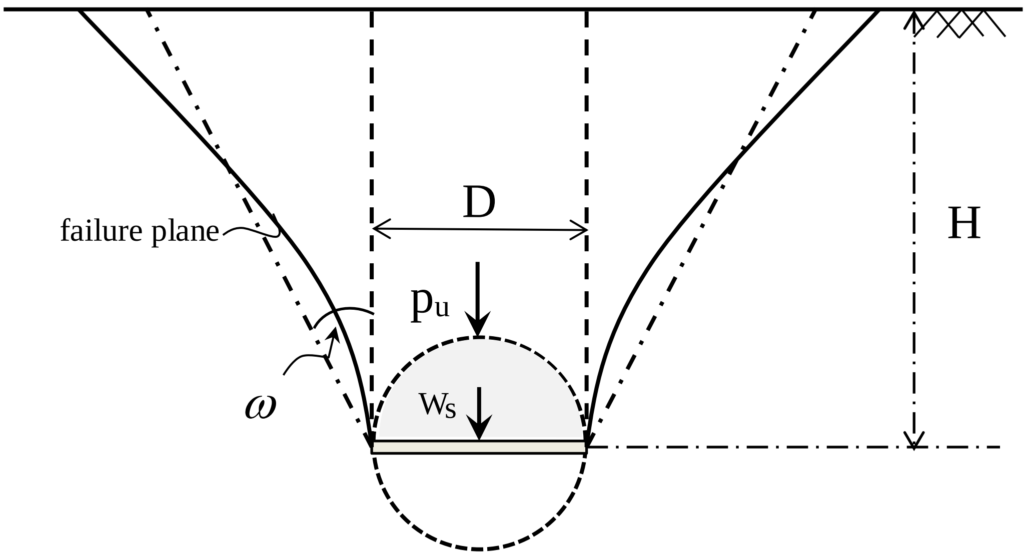
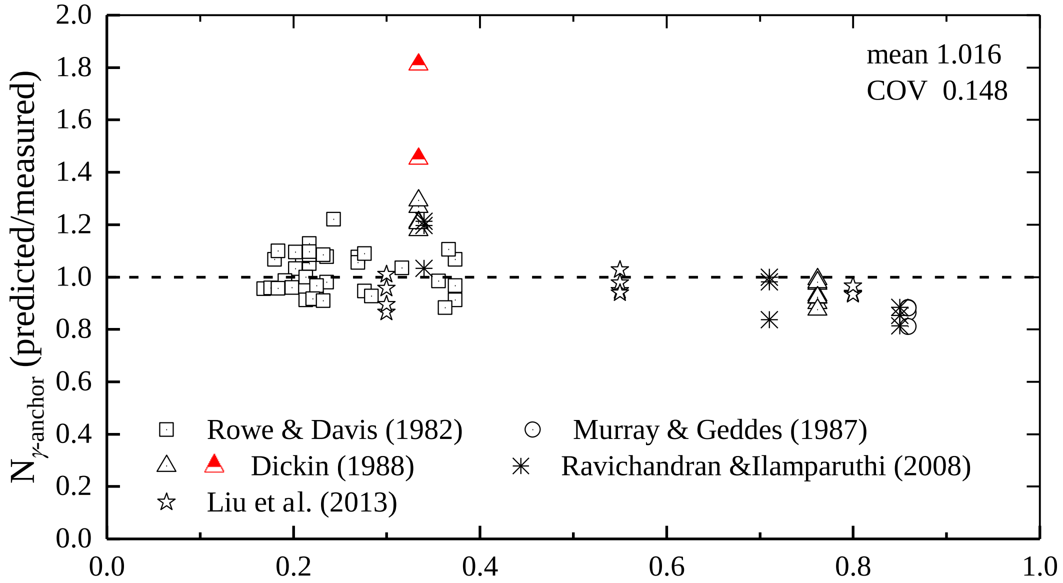
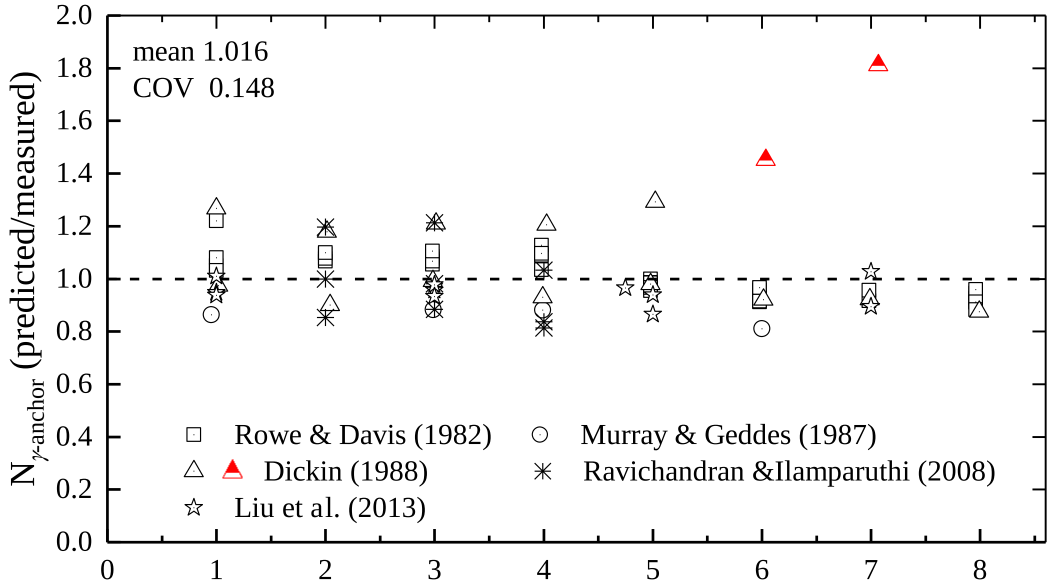


Fig. 1 Strip anchor geometry and simplified failure patterns



(a) Relative density (D_r)



(b) Embedment ratio (H / D)

Fig. 2 Predicted (using measured φ summarised in Table 1) against measured anchor factors: (a) variation with relative density; (b) variation with embedment ratios

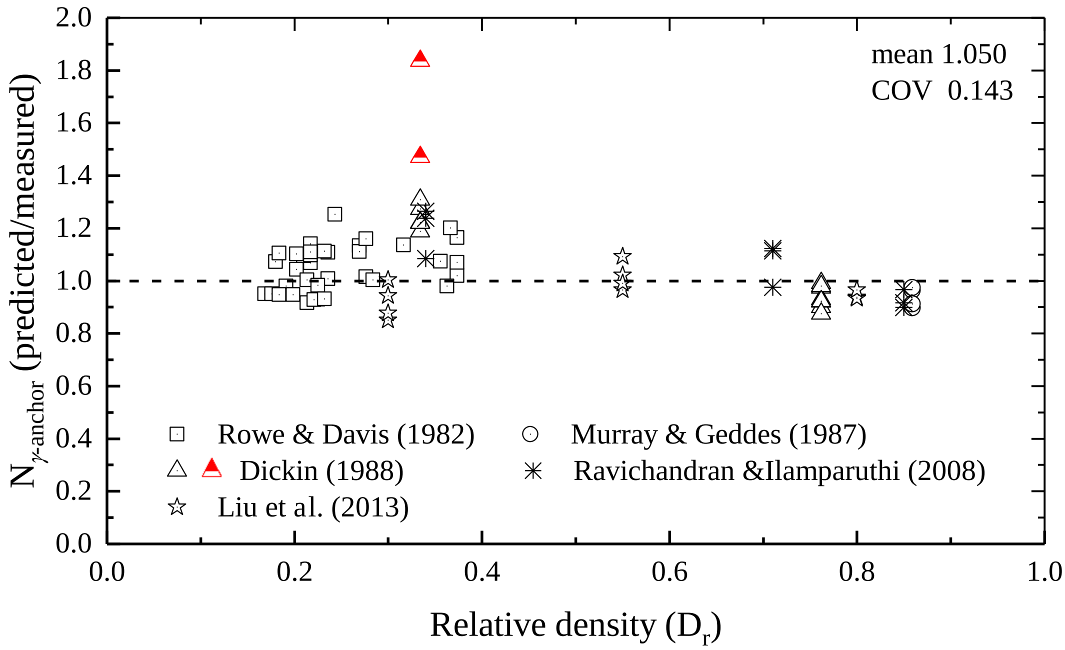


Fig. 3 Predicted (approximating φ with φ_{peak} calculated by equation (5)) against measured anchor factors

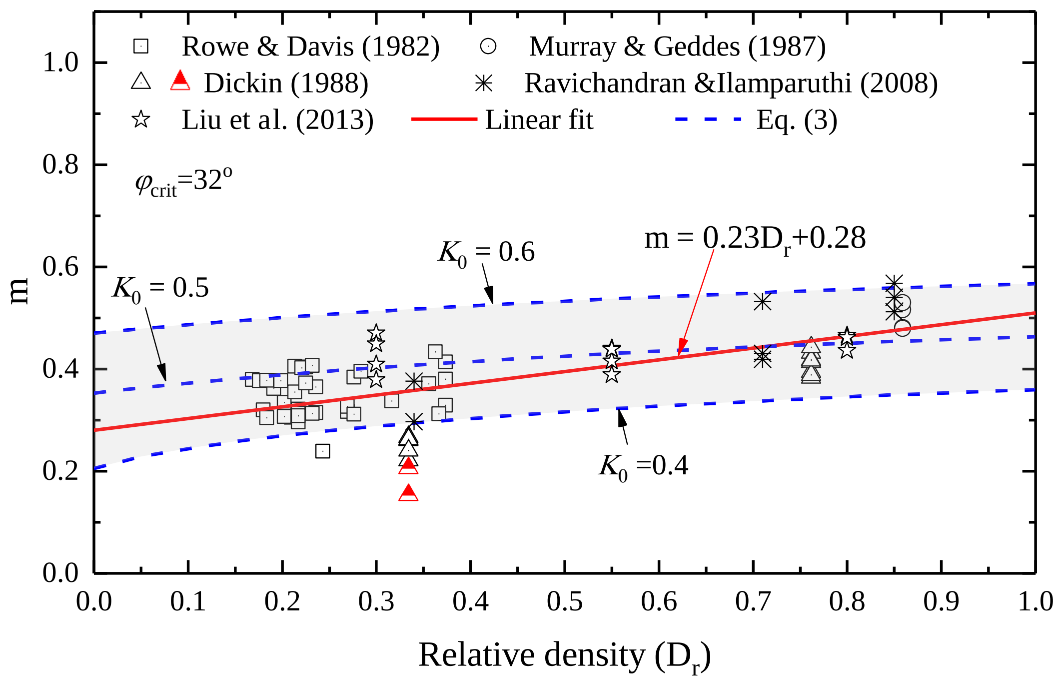


Fig. 4 Back-calculated (using measured anchor factors and equation (2)) and predicted (using equations (3) and (5)) values of m

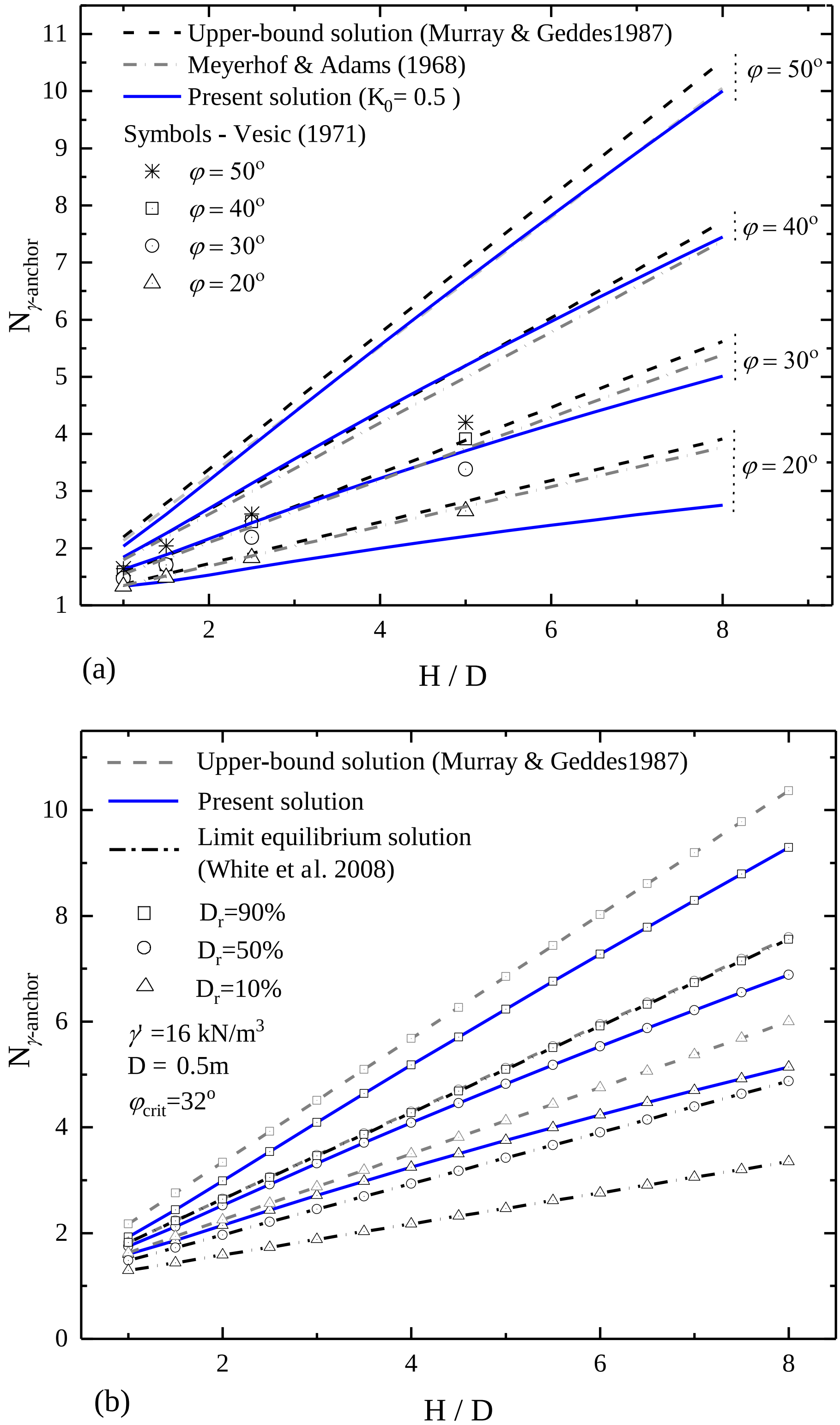


Fig. 5 Comparison with other solutions: (a) with given effective friction angles; (b) with peak friction and dilation angles calculated by Bolton's (1986) correlations