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Effect of Embedment Depth and Pullout Angle on the Movement of Model Suction Anchor

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Abstract:
In the offshore areas, the engineers are adopting modern construction practices with novel offshore foundation technologies to ease the installation process as well reduce the construction cost. Now a days wind power has gained priority as compared to the coal-based power generation. In the offshore, there is a huge scope for generation of wind-based power. The foundations of wind turbines in the offshore can subject loads coming from water waves, current, vibrations and dead loads. The water depth at places where wind turbines are to be installed varies from 20 to 60 m and it leads to huge cost for construction of conventional foundations. In order to overcome the difficulties associated with construction and high costs of installation of foundations, a novel foundation technique named 'suction anchor foundations' has evolved in the recent past. It is simple to install and minimizes the cost as well as construction time of the project. In the offshore, mostly sand and soft clay deposits predominantly present. In this paper, the study carried out on model suction anchors of L/D = 1, 1.5 and 2 in sand bed are discussed. The anchor aspect ratio L/D is defined as it is the ratio between anchor embedment depth to its diameter. The sand bed was prepared in a test tank corresponding to a 40% relative density of sand. In order to study the pullout movement of anchor, the pullout angles considered are 30°, 45°, 60° and 90°. The model anchors were installed in a prepared sand bed by pumping out the water from inside the anchor with the help of quarter HP centrifugal pump. The results revealed that the anchors pulled with lower pullout angle are taking higher pullout loads to cause a movement in the anchors and it is attributed to enhanced passive resistance from soil. Also, the embedment depth of anchor offered better resistance to movement of anchor.

Keywords: Suction anchor, embedment depth, pullout angle, cohesionless soil.

1. Introduction

In the recent years, focus is being made on to the exploration of marine resources for catering the needs of increased population. Demand for marine resources and wind energy has gained importance of offshore construction and different foundations for offshore structures. Suction anchor foundations are found best and economical options for the offshore structures in order to sustain the huge loads due to dead weights and ocean waves. The seabed soils in the deep-water areas, where offshore structures are to be installed mostly consists of sand and soft clays. Under large environmental loads the anchor foundations experiences high tensile loads. In order to meet the serviceability requirements of suction anchor foundations, the storm loads and in turn the tensile loads are required to be kept in permissible limits. It enables the minimal displacements. In the process of improving anchorage systems for military submarine applications, the engineers thought about an inverted `cup' subjected to vacuum would be of possible solution to solve the anchoring problem.

Suction caissons are embedded anchors into seabed and are used for offshore floating facilities. The diameter of cylindrical anchors, varies typically in the range of 3 to 8 m. These anchors are open at the bottom and closed at the top, with a length to diameter aspect ratio L/D in the range 3 to 6. When these foundations are treated as intermediate foundations, the L/D ratios would be about 1 and when treated them as deep-piled foundations, the L/D ratio would be up to 60.

These anchor foundations are called as suction anchors because with the assistance of suction, installation is carried out. The diameter to thickness ratio (D/t) of these anchors shall vary from 100 to 250. In order to avoid the buckling failure of the anchors during their installation, internal stiffeners are provided (Susan and Clukey, 2018). The suction piles and suction anchors are versatile, effective, and environmentally friendly foundation systems in the offshore constructions. To see the longevity of these foundations, the load resisting mechanism, installation, and design aspects are required to be carefully studied. There is a tremendous need to analyze the offshore suction anchors in the areas of breakwater systems utilizing gravity-type concrete caisson superstructure on top of concrete suction piles; a floating breakwater system utilizing embedded suction anchors; and a foundation system utilizing suction piles for temporary mooring of underwater tunnel elements (Bang et.al., 2009).

Several investigations were conducted on the capacity of suction anchors in various soils. In the recent past the suction anchors have gained popularity to use foundations in the offshore wind mill projects. Suction anchors may not be feasible to install sometimes due to presence of soil profiles that have sand overlain by layers of silt. Pullout capacity of anchor foundation depends mainly on the suction developed underneath the anchor. The failure mechanism plays a vital role in fixing the upper limits of suction and pullout capacities.

The inclined loads applied at the face of the anchor foundation tend to reduce the rotation of suction anchor, resulting in more lateral capacity.

Sometimes it is required to conduct lateral load tests on suction anchor foundations by shifting the load application point from the mudline to midway between mudline and skirt tip in order to see the effect of load application point on load carrying capacity of anchor. Uplift capacity of a suction anchor can be estimated using a three-dimensional upper bound analysis for different depths and angles of chain attachment. Shili Ma et.al (2023) conducted model tests to investigate the bearing capacities of tripod anchor foundations subjected to lateral loads in silty clay. Felipe et.al (2009) conducted experiments on dry sand at a low relative density to explore the drained response of the foundation.

The load characteristics resulting from the environmental impact, variation of site conditions, available construction and installation facilities would influence the design of the support structures. The support structure is to be designed to withstand not only the controlling extreme event, but also the effect of continuous cyclic loading on its operating behavior (Lesney, 2011). In the fields of single-point mooring systems, subsea structure bearing foundations and offshore windmill projects the traditional suction anchors would be preferred commonly. The suction anchors would provide required lateral and vertical bearing capacities and bending moment. In the recent years a wellhead suction anchor technology came into existence. In this technology, a a central pipe is added as a channel for drilling and further completion of operations involved. The bearing capacity design and overall size design is the main aspect in the design of the wellhead suction anchor. The size of the wellhead suction anchor, structural arrangement of the anchor and the mechanical properties of the topsoil of the construction block would affect the bearing capacity provided by the wellhead suction anchor. The design of wellhead suction anchors begins from calculating the loads applied to the wellhead suction anchors such as vertical loads, lateral loads and bending moment loads (Bo Li et. al., 2022).

Birch et. al. (2014) conducted small-scale experimentation using suction caissons having an aspect ratio (L/D) of 2.0 and studied the static and cyclic pullout behaviour. From static pullout testing, the failure strain, adhesion factor and reversed end bearing factor are ascertained. The cyclic pullout tests also conducted to establish the suction anchor capacity by simulating the loading and unloading system as due to wind and wave. The values for adhesion and reversed end bearing factors back calculated from the model test results revealed that they are smaller than the values suggested in design guides.

Rao et al. (1997) conducted series of model tests in the laboratory for varied liquidity index of Indian marine clay for both the open-top and closed-top suction caisson anchors and presented the pullout load capacities, variation of adhesion factors and bearing capacity factors. In suction anchor installation, pumping of water creates a differential pressure across the anchor top that pushes the anchor into the seabed deposit of required depth. This technology eliminates the need for pile driving. Still many uncertainties are present in the design of suction anchors foundations. The axial capacity of suction caissons mainly depends on the following aspects such as rate of loading, drainage length, hydraulic conductivity, and shearing strength parameters of soil. Due to the volume change characteristics of surrounding soils, the suction pressure will undergo changes during pullout of anchor. Test results revealed that the utilizing suction mechanism caissons can be installed effectively. Suction pressure present inside the anchor resists the part of axial tensile loads (Magued et.al., 2011).

Prediction of uplift capacity becomes difficult because of stress variations developed during uplift movement of suction caisson. In order to account the stress variations in uplift capacity calculation, studies are carried out considering soil stress release and differential pressure contribution. Series of numerical simulations were analyzed in sand, and the same is verified with the help of centrifuge model test results. Various soil drainage conditions during caisson being pulled out were considered in series of tests. Uplift capacity calculation method is proposed based on the analysis of simulations carried out in the study. Proposed method contributes to the more accurate assessment of uplift capacity of suction caisson in sand (Chenggen et. al., 2022). Seawall protects the coast and nearby infrastructure. There is a need to provide effective seawall in order to control the associated damages due to rising sea level. The suction caisson foundation would enhance the load carrying capacity of seawalls compared to the other coastal defense systems are constructed on soft marine deposits. The suction caissons are technically feasible and economically viable to be installed into marine clay layer as foundations. When suction caissons used as part of the foundation system for seawall might provide an economical method of installation where water depth is relatively deeper. Hao et. al (2022) proposed the conceptual design and procedure of construction for seawall on suction caisson foundation especially on soft marine clay. As per the in-place performance of the caisson is concerned, the installation procedure is required to be well understood in design of the caissons. Houlsby and Byrne (2005) presented the calculations appropriate for the installation of caissons in sands. These calculation methods are developed mainly to determine the resistance to penetration of open-ended caisson foundations by accounting the suction and without suction.

Due to the cost and time constraints of centrifuge and other physical model testing, it is usually not feasible to study experimentally and in great detail the effects of the various parameters such as anchor L/D ratio, the load application point D/L, pullout angle θ and the soil strength. Literature review revealed that the failure mechanisms developed under different loading rates are not well understood. The influence of anchor L/D ratio has also been not adequately reported. In this paper, pullout response of model suction anchors which were embedded in sand bed prepared in test tank is presented for anchor L/D ratios 1, 1.5 and 2. The anchors were installed in the sand bed by creating suction with the help of quarter HP centrifugal pump.

2. Experimental Work

The basic properties of soil are presented in Table.1. The medium to fine sand is present in the soil with a specific gravity 2.67. The sand was prepared in the test tank at a relative density of 40%. To maintain the relative density 40%, the sand best was tamped with wooden hammer at a dry density of 15.8 kN/m^3. The dry densities of sand corresponding to loose and dense states are 14.8 kN/m^3 and 17.6 kN/m^3 respectively.

A test tank of size 1.08m x 0.62m x 0.4m was utilized for testing of model anchors. A water of height 0.2m was kept above the sand bed for creating required suction underneath the anchor top for its installation. Through a fixed steel frame, a rope and pulley system were arranged to pull the anchor at required pullout angles. The pullout loads were applied through a hanger system arrangement. The anchor geometry and test tank set up is presented in Fig.1(a to c). The anchor in the test tank was placed in such a way that the distance from the anchor front face to the wall in the pullout direction is at least 6 times the size of the anchor to avoid the wall effects. The anchor embedment depth to diameter ratios (L/D) adopted in the study are 1, 1.5 and 2. The anchors were statically pulled up with pullout angles 30°, 45°, 60°, and 90°. The anchor which is made up of mild steel pipe has diameter 10 cm. At the top of an anchor a hole is made to create a suction inside the anchor, with the help of quarter HP pump. The model anchor was installed in a prepared sand bed by draining the water from inside the anchor with the help of quarter HP pump.

Table 1: Basic properties of sand

S.No.	Soil property	Value
1	**Grain size distribution** % Gravel % Coarse sand % Medium sand % Fine sand % Silt and clay	 0 0 65 35 0
2	Specific gravity, G	2.67
3	Dry unit weight, γ_d in kN/m^3 Minimum Dry Unit Weight, γ_{dmin} in kN/m^3 Maximum Dry Unit Weight, γ_{dmax} in kN/m^3	15.8 14.8 17.6
4	Density index, I_D	0.4

Fig 1: (a) Anchor geometry and (b) Tank and test set up (c) Pullout movement of anchor

(a) (b) (c) Progress of anchor pullout

3. Results and Discussion

Offshore oil and gas exploration and tapping of wind power gained popularity in the recent past. Selection of foundations for offshore structures depends on installation process, stability and economy. Suction anchor foundations are found very novel foundation technique to resist uplift loads and lateral loads coming on to the structure. Driving a pile foundation in an offshore environment, where water depth ranging between 100 to 300 m is difficult task and takes more of time for construction. In this paper the results of a laboratory tests conducted on model suction anchors embedded in loose sand are presented in the following sections.

Influence of Pullout Angle on Load Displacement Behaviour

The results of pullout load - displacement for anchors of L/D = 1, 1.5 and 2, for pullout angles θ = 30°, 45°, 60° and 90° are presented in Figs. 4.1 to 4.3. Fig.4.1 presents the load displacement curves for suction anchor embedment length of L/D = 1. From this figure, it is observed that up to about 10N load, the displacement of suction anchor is hardly 0.1 to 0.2 mm for all the pullout angles θ = 30° to 90°. From 10N pullout load onwards for any small increase in load the displacement f anchor is found to be mobilized gradually. In this figure, it is further noticed that the anchor pulled vertically i.e., θ = 90° case, the load - displacement curve is moving above the load - displacement curves of pullout angles θ = 30°, 45°, and 60°. In general, the anchor which is pulled vertically shall have less pullout load as compared to the anchor pulled with some inclination. This is because, when the anchor pulled with certain inclination, the mobilization of passive resistance increases and it results in application of more pullout load. In case of vertically pulled anchor, there may not be passive resistance mobilization and hence less load is required to pull the anchor. But, for the present condition, the anchor which is pulled vertically is showing higher pullout load compared to the anchor pulled with inclination. This can be attributed due to suction present between the anchor cap below and top of soil plug is holding the anchor downward. Fig.4.2 presents the load – displacement curves for anchor embedment depth L/D = 1.5 and for various pullout angles. From this figure, it can be seen that absolutely no pullout movement in anchor is observed up to about 20N of load and from 20N onwards almost in all the cases of pullout angles, there is a gradual movement in the anchor. The movement is observed very quick in case of anchor pulled with 90° inclination i.e., vertical. Upward movement of anchor for a given load is in slow rate as the pullout angle decreases from 90° to 30°. This can be attributed to mobilization of passive resistance at low pullout angles and it is causing higher pullout loads to make a movement in the anchor.

Fig.4.3 presents the load – displacement curves for anchor L/D = 2, and for various angles of pullout. In every angle of pullout, it is observed that up to a load of 30 N, the movement of anchor is almost negligible and from 30N load onwards even for small increase in load application, the movement in the anchor is gradual. From these curves, it is further noticed that as the pullout angle increases from 30° to 90°, the pullout load required is decreasing for a given displacement. From this figure, it can be further seen that up to a 6 mm displacement, the movement in anchor is gradual. After reaching a 6 mm of displacement, even for small increase in load, the movement in anchor is gradual and leading to sudden failure in the anchor.

Fig.4.1: Load – displacement curves for anchor L/D =1 and embedded with suction

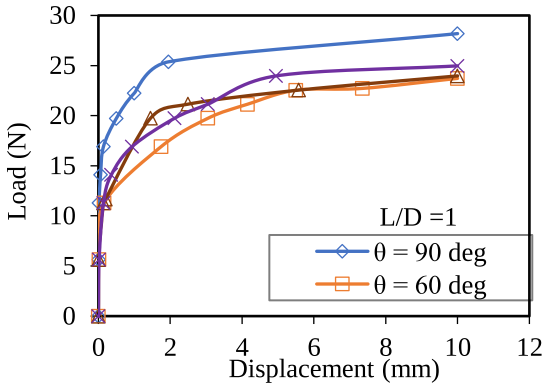


Fig.4.2: Load – displacement curves for anchor L/D = 1.5 and embedded with suction

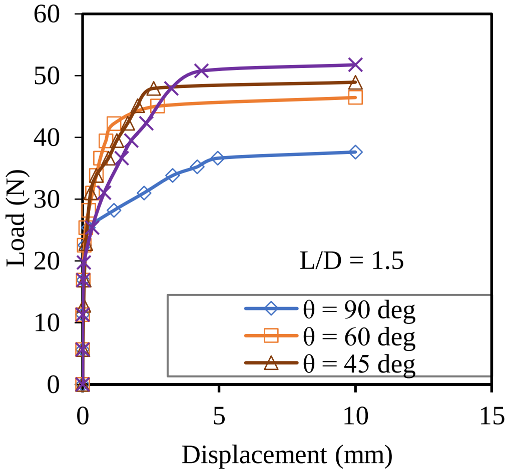
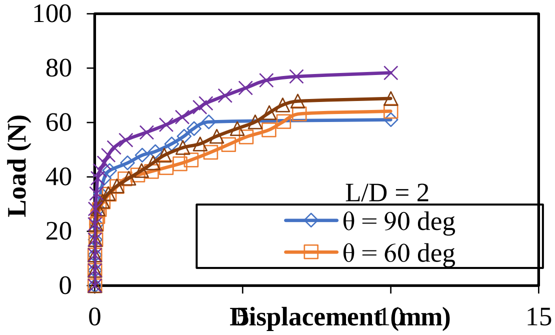


Fig.4.3: Load – displacement curves for anchor L/D = 2 and embedded with suction



From the curves presented in **Figs.4.1** to **4.3** it is mainly observed that the anchor pullout angle is influencing the pullout movement of anchor. The movement against the pullout loads is not drastic in the anchors installed with the aid of suction. This can be attributed as the suction present in the anchor is holding the anchor system not to fail immediately. Once the anchor is pulled out, the suction is gradually disappearing and hence the movement observed in the anchor is gradual and leading to failure.

Influence of L/D on Pullout Behaviour of Anchors

To understand the influence of anchor embedment depth, L/D on the pullout behaviour of anchor, a laboratory study was conducted considering the anchor embedment depths in the form of L/D ratio varying from 1 to 2 and the results obtained are presented in Figs.4.4 to 4.7. These results are pertinent to the anchors installed with the application of suction pressure. **Fig.4.4** presents the load – displacement curves for anchors L/D = 1, 1.5 and 2 for angle of pullout 90°, i.e. vertical pullout. This figure shows that nearly 15N applied pullout load the anchor movement is negligible and from 20N onwards the movement is gradual in the anchor whose L/D = 1. In case of anchors L/D = 1.5 and 2, the movement in anchor is gradual for the pullout loads of 30N and 40N onwards respectively. The anchor L/D = 1.5 showed faster movement from 38N pullout load onwards and for anchor of L/D = 2, the same faster movement in anchor is noticed at a load of about 60N onwards. From this figure, it is further noticed that at about 2mm displacement of anchor, the load levels are 25N, 30N and 50N respectively for anchors of L/D = 1, 1.5 and 2.

Fig.4.5 presents the pullout load movement curves for anchors of L/D = 1, 1.5 and 2 and for pullout angle θ = 60º. From this figure, it can be seen that the curves corresponding to L/D = 1.5 and 2 are moving almost parallel up to about 45N of pullout load and there after even for small increase in load resulting the faster movement in anchor L/D = 1.5, whereas in case of L/D = 2, the anchor has started moving up continuously after 60N pullout load. From this figure, it can be further observed that for a specified displacement of 6mm, the pullout load levels observed are 24N, 45N and 58N respectively for anchors L/D = 1, 1.5 and 2.

Fig.4.4: Load – displacement curves for pullout angle θ = 90^0 and for anchors embedded with suction

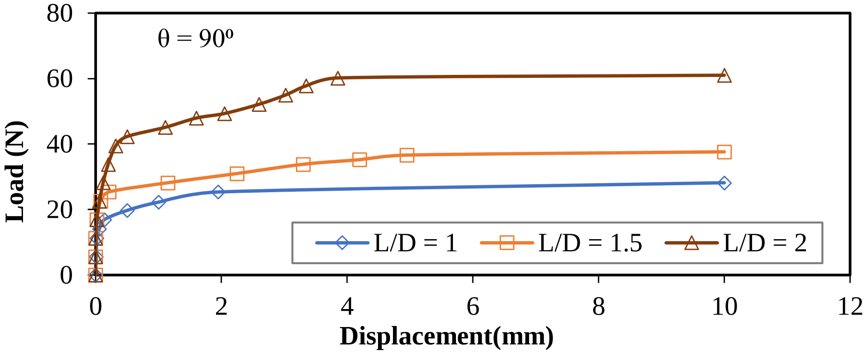


Fig.4.6 presents the movement of anchors L/D = 1, 1.5 and 2 for pullout angle of 45º. In this figure, it is noticed that the movement of anchors with pullout loads is following the similar trend as is seen in for pullout angle of 60º. The anchors pulled with inclinations 60º and 45º, showed not much difference in the pullout load for causing a similar movement in anchors. For instance, corresponding to an anchor movement of 6 mm in L/D = 2, the pullout loads at pullout angles 45^{0} and 60^{0} observed are 65 N and 58 N respectively. This indicates that the mobilization in passive resistance is almost same amount for the pullout angles, θ = 45º and θ = 60º. **Fig.4.7** presents the movement of anchors pulled with load inclination of 30^{0}. It can be seen that as the embedment depth increases, there is a clear increase in the pullout load. As compared to other pullout angles such as θ = 90º, θ = 60º, θ = 45º (**Figs.4.4** to **4.6**), the movement or displacement can be clearly distinguishable in case of pullout angle θ = 30º. This can be attributed that the mobilization of passive resistance is more for the case of anchor which is pulled with a pullout angle, θ = 30º. For a specified movement 6mm of anchors L/D = 1, 1.5 and 2, the pullout load levels observed are 25N, 50N and 76N respectively. From these observations, it is noticed that the anchors which are pulled at pullout angle θ = 30º, the load levels are 2 times and almost 4 times for the anchors of embedment depths 1.5 and 2 as compared to anchor L/D = 1.

Fig.4.5: Load – displacement curves for pullout angle θ = 60^{0} and for anchors embedded with suction

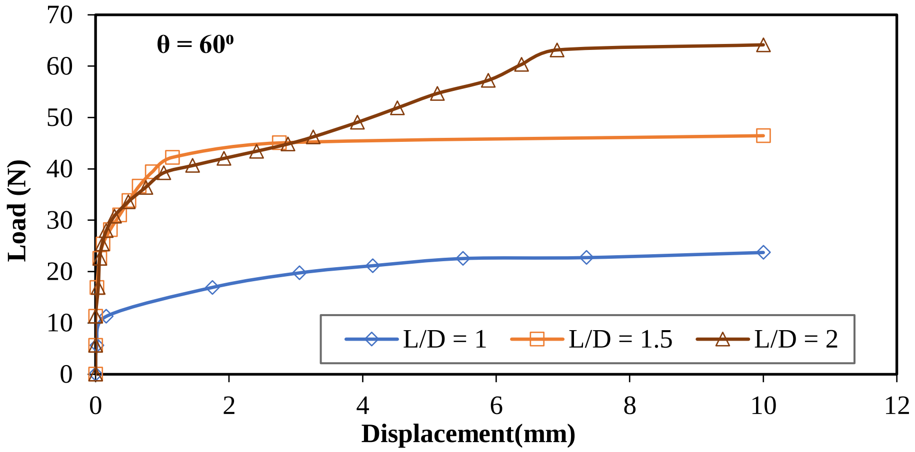


Fig.4.6: Load – displacement curves for pullout angle θ = 45^{0} and for anchors embedded with suction

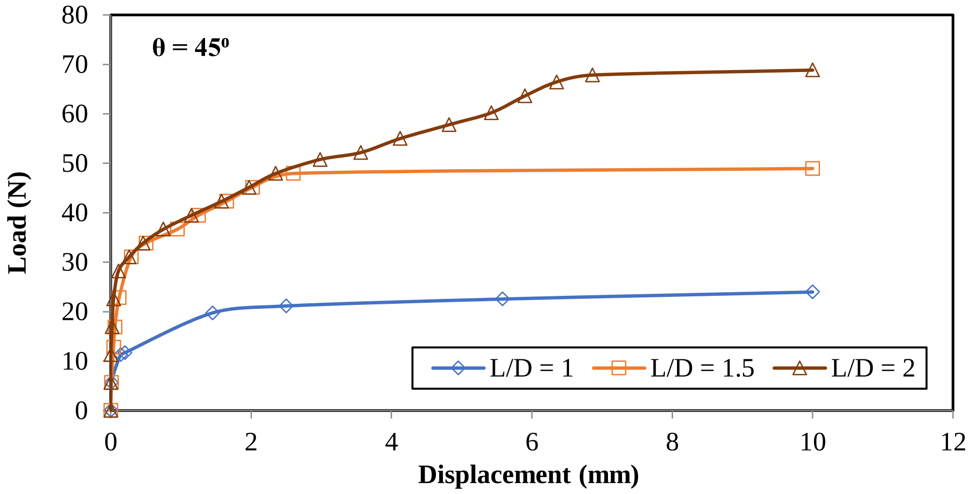
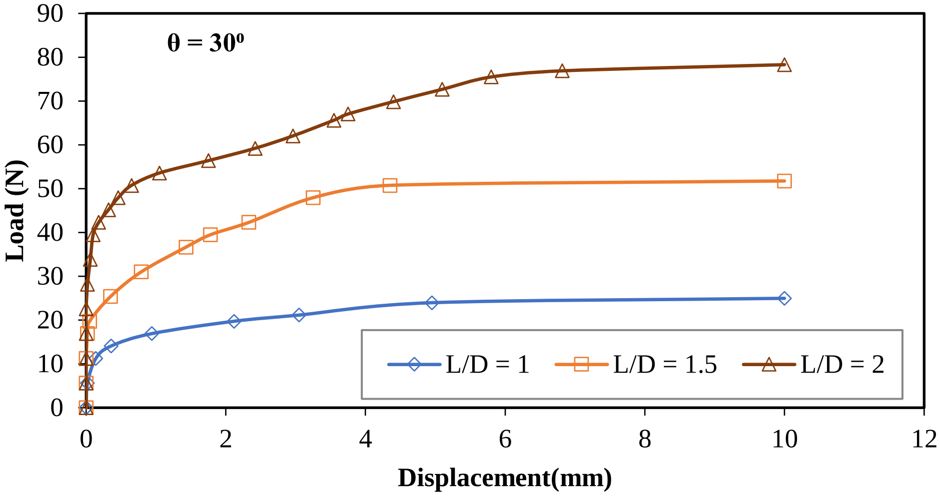


Fig.4.7: Load – displacement curves for pullout angle θ = 30^0 and for anchors embedded with suction



4. Conclusions

The pullout displacement (movement) observed is dependent on the size of the anchor and its embedment depth. Also, the soil density plays a vital role in causing a movement in the anchor. The pullout angle measured with the horizontal plane also playing a vital role in developing the pullout movement of anchors. The anchors pulled with lower pullout angles showed higher load levels in causing the movement in the anchors. Initially, the anchors showed resistance against the movement due to the presence of suction between bottom of anchor cap and top of soil plug. The anchors of L/D = 1.5 and 2, pulled with 30^0 angles showed the load levels respectively 2 times and 4 times higher than the load levels of anchor L/D =1. The increased embedment depth of anchor resulted in higher passive resistance and hence performing better in terms of load carrying capacity.

References

1. Bang, S., K. D. Jones, Youngryung Cho and D. J. Kwag (2009). Suction Piles and Suction Anchors for Offshore Structures. The Journal of the Deep Foundations Institute 3(2), Pages.3-13, DOI:10.1179/dfi.2009.007.
2. Birch Teodosio, Y., Kim, J., Ahn and I.T. Kim (2014). Model Tests of Suction Caisson Anchors: Reviews and Preliminary Results. Geo-Shanghai 2014, DOI:10.1061/9780784413425.031.
3. Bo Li, Bei-bei Kou, Bin Li, Jing Li, Jing Zeng, Qing-lei Niu, Yu-tao Shao, Ke-wei Zhang, Hao-yu Yu, and Ying-sheng Wang (2022). Application of wellhead suction anchor technology in the second production test of natural gas hydrates in the South China Sea. China Geology, Volume 5, Issue 2, April 2022, Pages 293-299.
4. Chenggen Xu, Haitao Jiang, Mengtao Xu, Decheng Sun and Shengjie Rui (2022). Calculation Method for Uplift Capacity of Suction Caisson in Sand Considering Different Drainage Conditions. Sustainability 15(1), DOI:10.3390/su15010454.
5. Felipe, A. Villalobos, B. W. Byrne and G. T. Houlsby (2009). An experimental study of the drained capacity of suction caisson foundation under monotonic loading for offshore applications. Soils and Foundations, Vol.49, No.3, 477- 488.
6. Hao Chen, Jian Chu, Wei Guo and Shifan Wu (2022). Use of suction caissons for seawall construction. Ocean Engineering, 266(1–4):112632, DOI: 10.1016/j.oceaneng.2022.112632.
7. Houlsby, G. T., and B. W. Byrne (2005). Design procedures for installation of suction caissons in sand. Proceedings of the

Institution of Civil Engineers - Geotechnical Engineering, Volume 158 Issue 3, July 2005, Pages. 135-144, ISSN 1353-2618 | E-ISSN 1751-8563, doi.org/10.1680/geng.2005.158.3.135.

8. Lesny, K., W. Richwien (2011). Design, construction and installation of support structures for offshore wind energy systems. Wind Energy Systems, Optimizing Design and Construction for Safe and Reliable Operation, Woodhead Publishing Series in Energy, 2011, Pages 479-518.
9. Magued Iskander, Sherif El-Gharbawy and Roy Olson (2011). Performance of suction caissons in sand and clay. Canadian Geotechnical Journal, 39(3): Pages. 576-584, DOI:10.1139/t02-030.
10. Rao, N.S., Ravi, R., and Prasad, S.B. (1997). Pullout behavior of suction anchors in soft marine clays. Marine Geosources & Geotechnology, Taylor and Francis, London, 15:2, Pages. 95-114.
11. Shili, M. A, Liquan, X. I. E, Tsung-Chow, S. U. (2023). Model testing of tripod caisson foundations in silty clay subjected to eccentric lateral loads. Front. Struct. Civ. Eng. Vol. 17, Issue (3), Pp.467-476, DOI: 10.1007/s11709-023-0933-6.
12. Susan Gourvenec and Ed Clukey (2018). Suction Caisson Anchors. Encyclopedia of Maritime and Offshore Engineering, John Wiley & Sons, Ltd., DOI: 10.1002/9781118476406.emoe581, ISBN: 978-1-118-47635-2.