FACTOR OF SAFETY FOR ASSESSING PUNCH-THROUGH FAILURE DURING INSTALLATION AND PRELOADING OF SPUDCAN FOUNDATIONS

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ABSTRACT
Installation and preloading of independent-legged mobile oil and gas drilling jack-up rigs and wind turbine installation vessels in seabed sediments where a strong layer overlays weaker soil can lead to catastrophic 'punch-through', with potential leg buckling or toppling of the unit. Factor of safety is one of the important assessment methodologies to evaluate the risk of rapid leg penetration or punch-through failure. McClelland Engineers (1983) first introduced the factor of safety concept defining two factors: (i) factor of safety, Fs = Q_{max} / V_{Lo} (maximum geotechnical bearing capacity of the strong layer/designed maximum preload to be applied); (ii) bottom layer holding capacity, Rp = Q_{min} (minimum bearing capacity of the weak layer)/ V_{Lo}. They plotted a FS - R_p design chart, dividing into four zones encompassing punch-through likely to occur to unlikely to occur. Later Senner (1993) improved the chart by slightly changing the failure envelopes for the four zones and adjusting horizontal (R_p) axis to begin at 0.5 instead of 0.0. This study has modified the failure envelopes further. The performance of the proposed modified design chart in estimating the likelihood of punch-through has been assessed by plotting field data from 29 case histories. Uncertainties and cautions have been highlighted.

The information presented in this paper is being considered by the ISO Panel 4 jack-up rig committee for adoption in the ISO 19905-4 guidelines. However, this information has not been accepted by the full committee and may undergo additional changes. The reader should use discretion when using this information as it may undergo further changes before being adopted by the committee.

KEY WORDS: Spudcan foundations; Installation and preloading; Layered seabed; Punch-through failures; Factor of safety; Oil and gas drilling jack-up rigs; Wind turbine installation vessels

INTRODUCTION

Oil and Gas Drilling Rigs

The offshore industry has conducted oil gas drilling operations over the last 7 decades. Most offshore drilling in shallow to moderate water depths was performed from self-elevating jack-up rigs due to their proven flexibility, mobility, and cost-effectiveness. Historically, DeLong Rig No. 1 was the first rig consisting of a rectangular barge supported by 6 tubular legs. In 1954, DeLong-

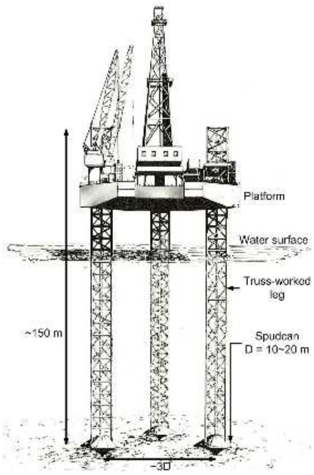
McDermott No. 1 was introduced. That was the 1st mobile offshore drilling platform. The barge had 10 tubular legs with a spudcan foundation at the bottom of each leg to prevent deep penetration of the leg into the seabed. In 1955, LeTourneu platform was designed featuring 3 electro-mechanically operated lattice type legs. These evolutions for the platform, legs, and foundations have continued (see Figs. 1a and 1b). Today's jack-ups typically consist of a buoyant triangular platform supported by three independent truss legs (of length 69 to 216 m), each attached to a large 10 to 20 m diameter inverted cone type or flat spudcan (Fig. 1e).

(a) Old oil and gas jack-up with tubular legs

(b) Modern oil and gas jack-up with truss legs

(c) Wind farm jack-up with tubular legs

(d) Wind farm jack-up with truss legs



(e) Supported spudcan foundations (Le Tirant, 1979)

(f) Supported spudcan foundations (Jin et al., 2019)

Figure 1. Oil and gas and wind farm jack-ups supported by spudcan foundations

Wind Turbine Installation Vessels

The offshore industry is now focusing on harvesting marine renewable energies through development of e.g. wind farms. Among several types (e.g., tugboat, heavy lift cargo ship, jack-up barge/vessel, semi-submersible with crane; Jiang, 2021), jack-up units (Figs. 1c and 1d) have been the primary choice for the installation of wind turbine components and for the installation of foundations, transition pieces, and offshore substations (J-REG, 2024). In addition, jack-up units are used to support operation and maintenance activities. Interestingly, the features of the modern jack-up barge/vessel are very similar to the first generation or olden days oil and gas drilling barges (Old is Gold!). It consists of a self-propelled platform (large deck), which is supported to the seabed by 4 to 6 tubular or truss legs (Figs. 1c and 1d), each attached to a large 6 to 15 m diameter spudcan (Fig. 1f; e.g., Mesa et al., 2023). The size of the wind turbine structures and output capacity are increasing rapidly. Development of wind farms have moved to new and challenging locations with deeper water depths and harsher environments with stratified seabed deposits.

Installation and Preloading
Barges and vessels (from here it will be referred to as jack-ups) are self-propelled or towed to the location and the legs are jacked down to pin the jack-up onto the seabed. Prior to commencing drilling or construction operations, the legs (and hence spudcan foundations) are preloaded either simultaneously or sequentially (one or two legs at a time) and in stages to about 150-200% of the nominal standing operating load. The designed maximum preload (V_{Lo}) is typically maintained for about 2 hours (Hossain et al., 2014). The preload is then removed, and the hull or barge is elevated to provide an adequate airgap for safe operation. This height depends on either clearing surface waves (which is assessed from the 50-year extreme weather criteria with an additional 1.5 m safety distance) and/or raising the crane to increase the lifting height.

Stratified Seabed: Potential for Punch-Through Failure
Jack-up preloading in stratified deposits, where a strong layer overlays weaker soil, has always been a challenge with the potential for rapid leg run or catastrophic 'punch-through' failure under the load-controlled conditions. This means the installing spudcans undergo abrupt and rapid penetration of more than several meters, which may lead to bending of a leg, structural failure of the leg leading to capsizing of the jack-up, colliding with the adjacent platforms or wind turbines, and fatalities in extreme cases. Two recent examples are illustrated in Fig. 2.

(a) Oil and gas jack-up sunk off Sarawak, Malaysia in May 2021

(b) Wind farm jack-up capsized in the South China Sea in July 2021

Figure 2. Recent examples of jack-up punch-through

RECENT INVESTIGATIONS ON SPUDCAN PUNCH-THROUGH
Seabed sediments with potential for soil related punch-through can broadly be categorised as (i) sand over clay, (ii) stiff over soft clay, (iii) crust over soil layers, and (iv) multilayer soils with surface or interbedded strong over weak layering. Based on the site-specific soil investigation data, if these layering systems are identified, cautions are exercised. Spudcan penetration resistance profiles are calculated using the methods suggested in ISO 19905-1 (ISO, 2024). Several investigations have been carried over the last two decades for improving the understanding through revealing the underlying soil failure mechanisms and for assessing spudcan penetration resistance profile, in particular, the peak or maximum geotechnical bearing capacity (Q_{max}) of the strong layer (e.g., Teh et al., 2008, 2009; Hossain et al., 2009, 2010a, 2010b; Lee et al., 2013a, 2013b; Hu et

al., 2013, 2015; Hossain, 2014; Zheng et al., 2016, 2017; Ullah et al., 2017a, 2017b). Hossain et al. (2014, 2019) have assessed the performance of the calculation methods suggested in ISO 19905-1 and the recently developed methods against some field installation data.

FACTOR OF SAFETY AGAINST PUNCH-THROUGH: EXISTING DESIGN CHARTS

Factor of safety is one of the important assessment methodologies to evaluate the risk of rapid leg penetration or punch-through failure. However, despite the development of jack-up rig guidelines over the last two decades (as discussed in the previous section), factor of safety against punch-through failure has barely been discussed even in the latest version of ISO 19905-1 (ISO, 2024) and J-REG (2024). McClelland Engineers (1983) first introduced the factor of safety concept. They established a typical load-penetration profile in a strong over weak soil profile that defined two critical factors assessed from the spudcan penetration curve as (see Fig. 3)

1. Factor of safety (Fs), which is defined as the ratio of the maximum soil bearing capacity in the top strong layer (Q_{max}) and the applied maximum preload (V_{Lo}), i.e., Fs = Q_{max} / V_{Lo};
2. Bottom layer holding capacity (Rp), which is the ratio of the minimum soil bearing capacity in the underlying weak layer (Q_{min}) to the applied maximum preload (V_{Lo}), i.e., Rp = Q_{min} / V_{Lo}.

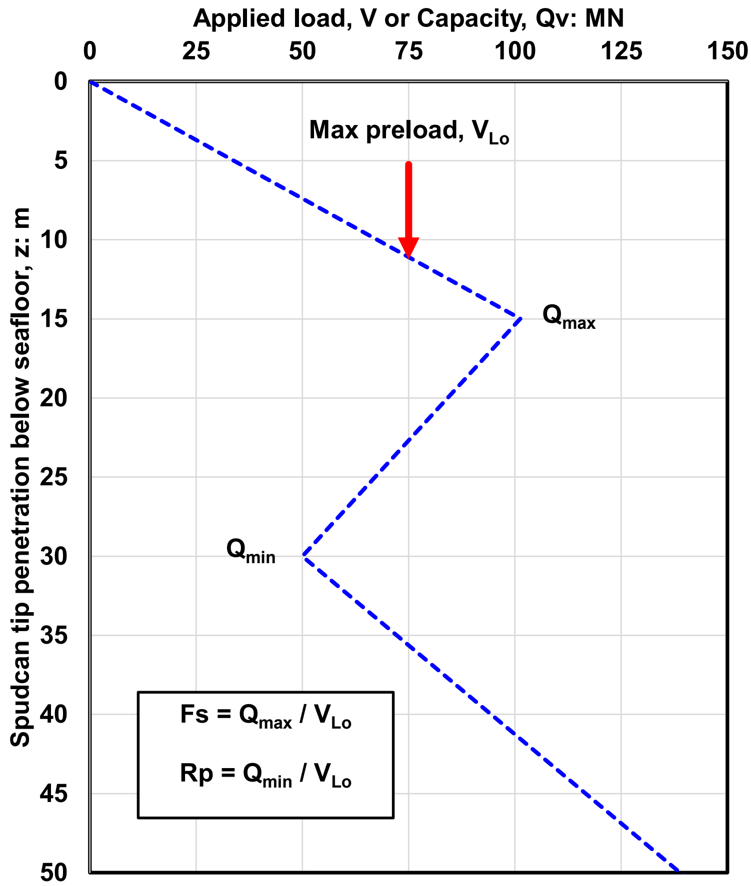
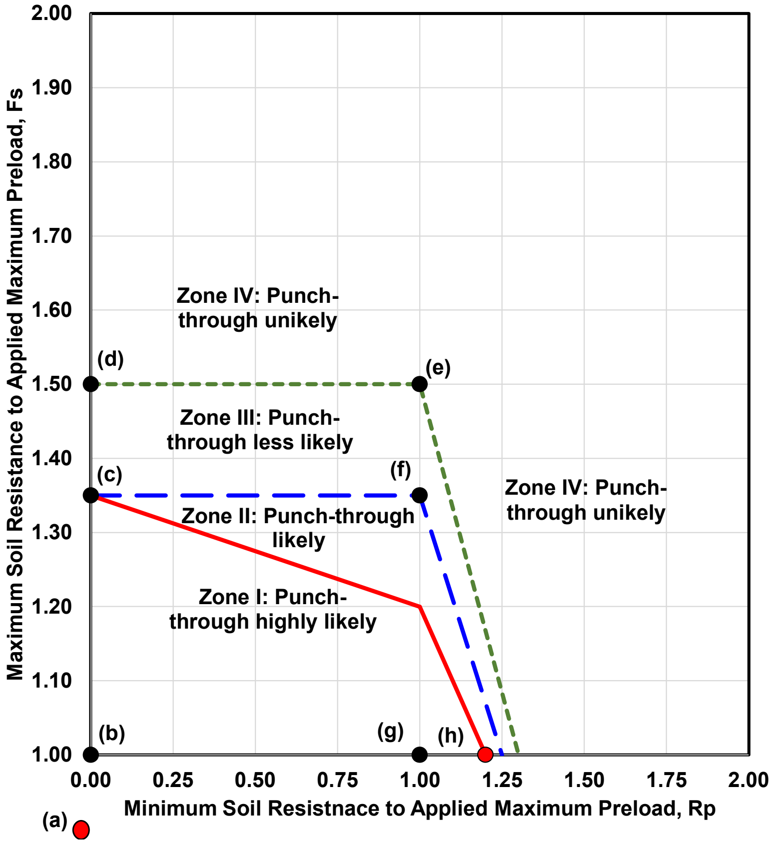
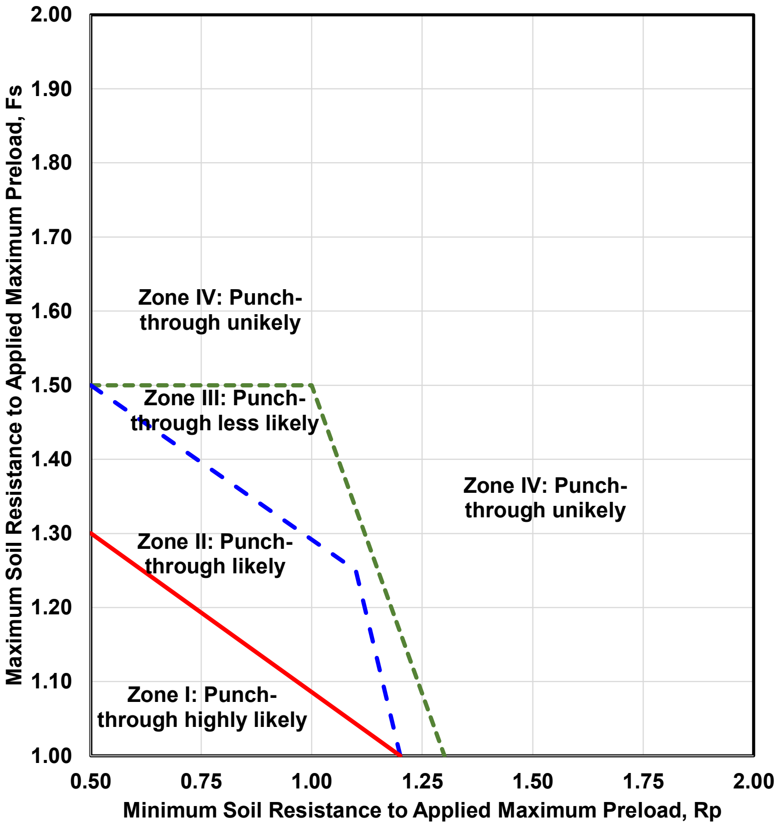


Figure 3. Assessment terms from spudcan penetration curve

A deign chart was drawn with axes consisting of Fs (starting from 1.0) and Rp (starting from 0.0), and with failure envelopes encompassing four zones ranging from high-risk of punch-through (Fs ≤1.35 and Rp ≤ 1.2) to low- or no-risk of punch-through (Fs > 1.5 and Rp > 1.3), as shown in Fig. 4a. Note, these recommendations were drawn based on the soil information from a single soil boring per site in the Gulf of America with corresponding field laboratory test data. Advanced laboratory test data and cone penetration test data were not available as the method was developed as an aid for an assessment made in the field, based on a borehole performed from the jack-up rig. Later Senner (1993) improved the chart by slightly changing the failure envelopes for the four zones and adjusting horizontal (Rp) axis to begin at 0.5 instead of 0.0 (see Fig. 4b). Four zones were marked indicating degree of punch-through possibility with no punch-through predicted for Fs > 1.5 and Rp > 1.3, similar to the McClelland recommendation.



(a) McClelland Engineers (1983)



(b) Senner (1993)

Figure 4. Existing factor of safety design charts

Renewable UK (2013) notes that to guard against punch-through in the elevated in-service condition, the V-H bearing utilisations obtained using unfactored loads and unfactored resistances should not exceed 0.67 (giving a safety factor of 1.5) based on vectors from the still water reaction. Dier et al. (2004) also confirmed this upper bound Fs of 1.5. Lipp (2021) and other researchers and engineers have also used these charts for evaluating the potential for punch-through failure.

FACTOR OF SAFETY AGAINST PUNCH-THROUGH: MODIFIED DESIGN CHART

To visualize (and understand) the above factor of safety charts, Points (a) to (h) have been labelled on the boundaries/envelopes in Fig. 4a, and corresponding typical leg penetration curves are plotted in Figs. 5a to 5h, respectively. The following features can be extracted

(a) For Fs < 1.00 and regardless of Rs (e.g., Fs = 0.75, Rp = 0.0; Point (a) on Fig. 4a and Fig. 5a), it can clearly be seen that punch-through is predicted to occur when applied preload V will be equal to Q_{max} before applying the targeted/designed maximum preload of V_{Lo}. As punch-through is very obvious for this case, both McClelland Engineers (1983) and Senner (1993) started the vertical or Fs axis from 1.0 in the factor of safety charts (see Fig. 4).

(b) For Fs = 1.00 and Rp = 0.0 (Point (b) on Fig. 4a and Fig. 5b), V_{Lo} lies on the verge i.e. $V_{Lo} = Q_{max}$, and punch-through is more likely to occur.

(c) For Fs = 1.35 and Rp = 0.0 (Point (c) on Fig. 4a and Fig. 5c), the strong layer is capable to hold V_{Lo} with the maximum capacity Q_{max} is 35% higher than V_{Lo}. Consequently, punch-through is less likely to take place for Fs ≥ 1.35.

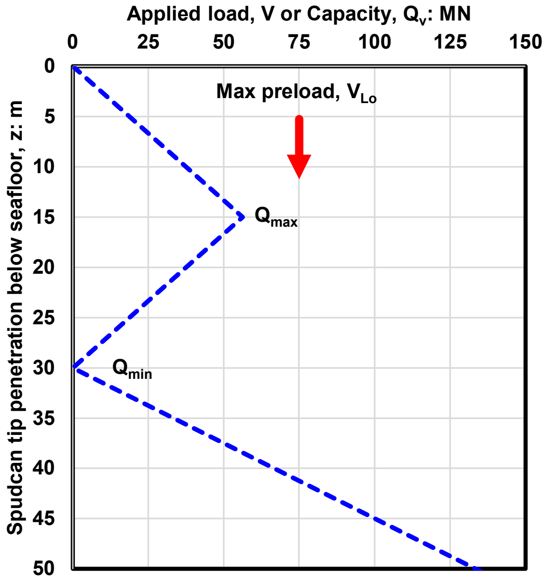
(d) For Fs = 1.50 and Rp = 0.0 (Point (d) on Fig. 4a and Fig. 5d), the strong layer is very well capable to support V_{Lo} with Q_{max} is 50% higher than V_{Lo}, giving confidence that punch-through is unlikely to occur for Fs ≥ 1.50. However, for the above cases, Rp = 0.0 means the minimum capacity (and hence strength) of the weak layer is 0, which is generally not the case unless the soil is liquefied (effective stress becomes 0). Therefore, Rp should generally be > 0.0.

(e) For Fs = 1.50 and Rp = 1.0 (Point (e) on Fig. 4a and Fig. 5e), the strong layer is very well capable to support V_{Lo} with Q_{max} is 50% higher than V_{Lo}. The weak layer is also just sufficient to hold V_{Lo} (i.e. $Q_{min} = V_{Lo}$) - punch-through is unlikely to occur for Fs ≥ 1.50 and Rp ≥ 1.0.

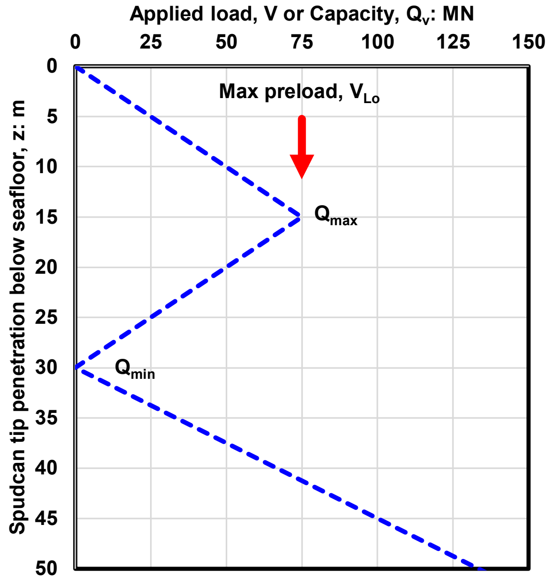
(f) For Fs = 1.35 and Rp = 1.0 (Point (f) on Fig. 4a and Fig. 5f), again punch-through is unlikely to occur for Fs ≥ 1.35 and Rp ≥ 1.0.

(g) For Fs = 1.00 and Rp = 1.0 (Point (g) on Fig. 4a and Fig. 5g), $V_{Lo} = Q_{max} = Q_{min}$, i.e., they all fall on the same line and hence there is a potential for rapid leg run, but not punch-through.

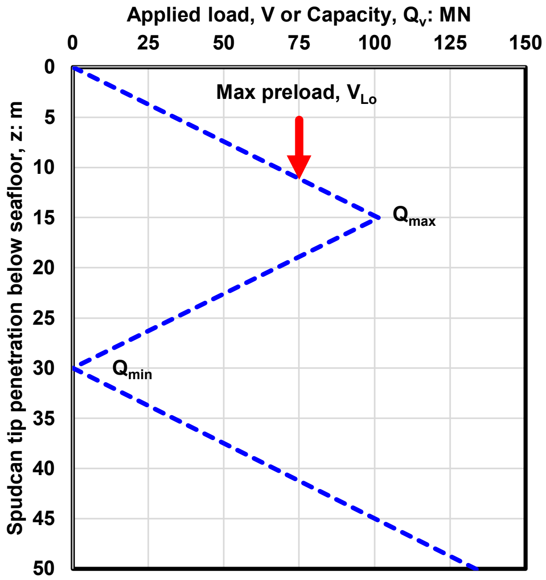
(h) Finally, for Fs = 1.00 and Rp = 1.2 (Point (h) on Fig. 4a and Fig. 5h), the minimum capacity of the weak layer (Q_{min}) is higher than the maximum capacity of the strong layer (Q_{max}), i.e., the weak layer is nominally stronger than the strong layer. This violates the consideration of strong over weak layering, and neither punch-through nor rapid leg run will occur. This point should therefore not be included in the chart.



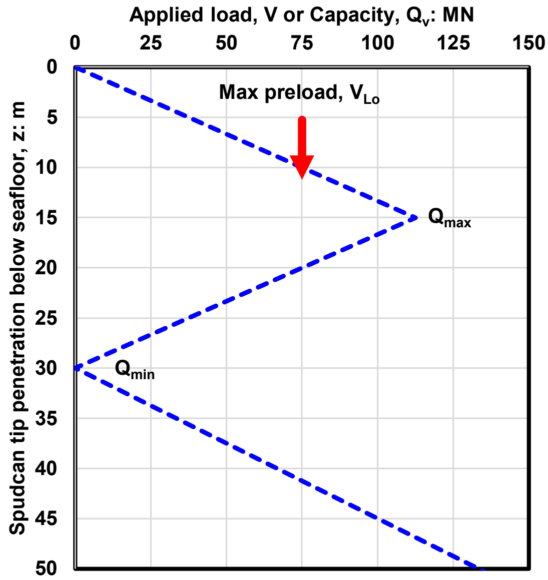
(a) Fs = 0.75, Rp = 0.0



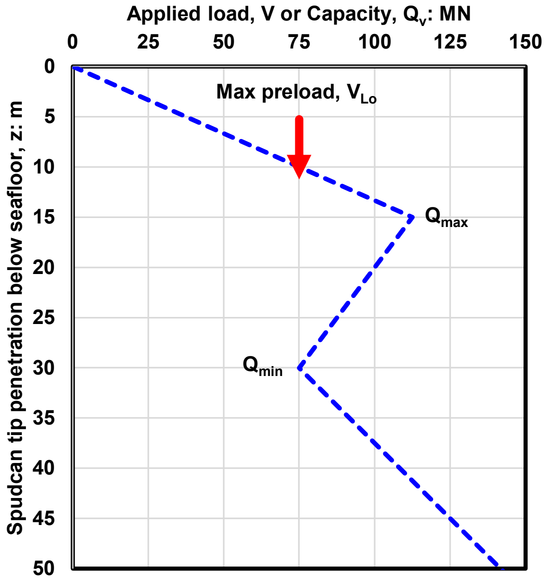
(b) Fs = 1.00, Rp = 0.0



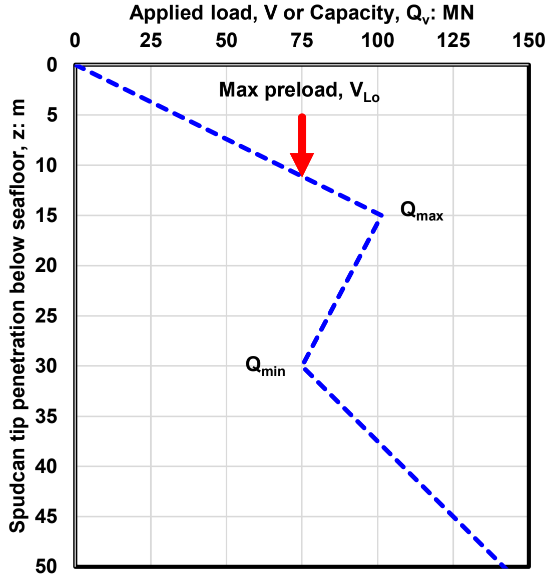
(c) Fs = 1.35, Rp = 0.0



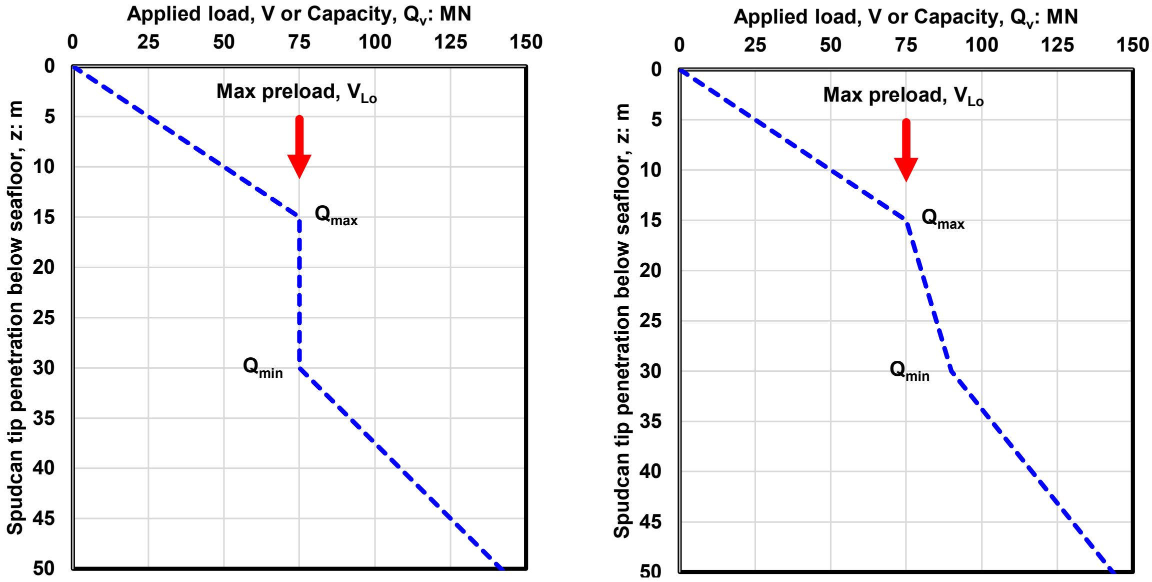
(d) Fs = 1.50, Rp = 0.0



(e) Fs = 1.50, Rp = 1.0



(f) Fs = 1.35, Rp = 1.0



(g) Fs = 1.00, Rp = 1.0 (h) Fs = 1.00, Rp = 1.2

Figure 5. Illustration of spudcan load-penetraiton profiles for various combination of Fs and Rp

Based on the above visual observations, the failure envelopes were modified, and an improved factor of safety design chart was proposed (see Fig. 6) to be used in practice.

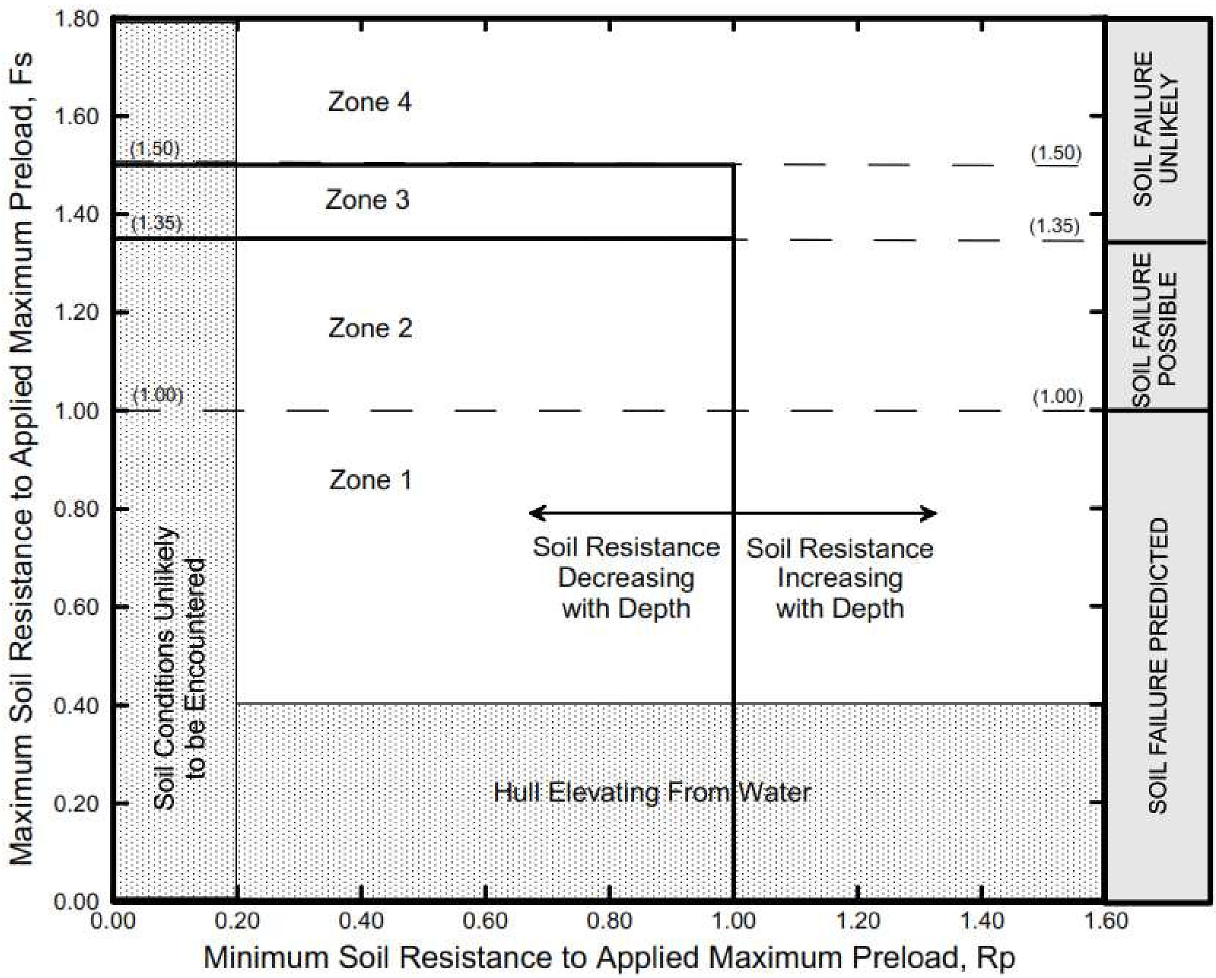


Figure 6. Modified factor of safety design chart

An explanation of the risk of failure for each zone in Figure 6 is explained in Table 1 below.

Table 1 Risk of punch-through failure for Zones 1 to 4

Zone	Risk category	Range of Fs and Rp	Comments
1	High	Fs ≤ 1.00 and Rp ≤ 1.0	Punch-through failure is predicted. If Q_{max} is low, the foundation will fail during early preload and be manageable. For foundation failure at or near the maximum applied preload, additional analysis including evaluation of punch-through analysis, and punch-through recovery analyses should be considered.
2	Moderate to High	1.00 < Fs ≤ 1.35 and Rp ≤ 1.0	Foundation failure is not predicted but could occur near the maximum preload (V_{Lo}) depending on the accuracy of the assessed load penetration profile. Additional analyses that include reduced maximum preload, punch-through analysis, and punch-through recovery analyses should be considered.
3	Low to Moderate	1.35 < Fs ≤ 1.50 and Rp ≤ 1.0	The possibility of punch-through failure depends on the accuracy of the assessed load penetration profile. The accuracy increases with additional site-specific geoscience data, and load penetration assessment using multiple bearing capacity analyses methods. The accuracy of soil conditions can be improved through multiple boreholes, companion cone penetration tests, high quality geophysical data, and historical spudcan penetration records.
4	Low	Fs > 1.50 and/or Rp > 1.0	Foundation is unlikely to fail based on available geoscience information. Additional analysis is not recommended.

PERFORMANCE OF MODIFIED FACTOR OF SAFETY DESIGN CHART

The performance of the modified factor of safety design chart has been assessed against 29 case histories collected from different locations around the world. The field installation and preloading records, as summarised in Table 2, are reported for the first time. Spudcan load-penetration response profiles (curves) were developed based on the site-specific soil data utilizing bearing capacity methods proposed by ISO 19905-1, and the corresponding Q_{max} and Q_{min} (and hence Fs and Rp) values were included in Table 2. Case histories were provided and spudcan penetration curves were developed by four different consultants.

Figure 7 plots the field data on the modified design chart, where

1. Red square: Punch-through potential identified but did not occur,
2. Blue triangle: Punch-through potential identified and occurred, and
3. Magenta circle: Punch-through potential not identified and did not occur.

It can be seen that, apart from the red squares (which are mainly because of poor site investigation data and hence spudcan penetration profile calculation), the assembled data confirm that the modified chart can be used for evaluating the potential of punch-through failure. Interestingly the data generally show a linearly increasing trend, with Rp always less than Fs. An Fs value of 0.4 represents the approximate ratio in which the Stillwater load falls for most rigs, below which the hull buoyancy limits the potential for damage from punch-through failure. An Rp value below 0.2 represents soil conditions that are unlikely to occur (typical for very soft weak layer). As such, soil data are unlikely to fall within that zone.

Table 2 Summary of 29 case history dataset

	D (m)	Q_{max} (MN)	Q_{min} (MN)	V_{Lo} (MN)	Fs	Rp
Case history 1	12.1	27	21	35.5	0.76	0.59
Case history 2	12.1	30.5	25.5	35.6	0.86	0.72
Case history 3	13.5	60	48	56	1.07	0.86
Case history 4	12.1	29	22	35.6	0.81	0.62
Case history 5	11.9	34	18	30.5	1.11	0.59
Case history 6	11.9	120	72	72.8	1.65	0.99
Case history 7	11.9	72	72	70.6	1.02	1.02
Case history 8	11.9	88.96	80.07	70.6	1.26	1.13
Case history 9	11.9	152	140	105	1.45	1.33
Case history 10	11.9	125	110	113	1.11	0.97
Case history 11	11.9	145.3	138	62	2.34	2.23
Case history 12	11.9	77.6	63.3	89.7	0.87	0.71
Case history 13	11.9	99.79	76.72	66.19	1.51	1.16
Case history 14	11.9	66.72	43.6	70.28	0.95	0.62
Case history 15	11.9	66.72	40	76	0.88	0.53
Case history 16	11.9	66.72	43	76	0.88	0.57
Case history 17	15.69	65.7	58.84	73.97	0.89	0.80
Case history 18	12.65	47.56	44.13	42.03	1.13	1.05
Case history 19	12.65	33.34	29.42	42.03	0.79	0.70
Case history 20	17.17	105.9	92.18	86.73	1.22	1.06
Case history 21	17.17	84.34	65.7	86.73	0.97	0.76
Case history 22	17.98	58.84	53	81.4	0.72	0.65
Case history 23	13.82	52.3	36.28	77.47	0.68	0.47
Case history 24	13.82	39.22	23.53	77.47	0.51	0.30
Case history 25	15.14	61.4	44.13	68.65	0.89	0.64
Case history 26	15.14	57.66	40.2	68.65	0.84	0.59
Case history 27	15.14	60.9	44.13	68.65	0.89	0.64
Case history 28	17.17	60.8	56.88	80.4	0.76	0.71
Case history 29	17.17	41.19	18.63	77.47	0.53	0.24

CAUTIONS

Punch-through risk assessment largely depends on the accurate assessment of Q_{max} and Q_{min} with a degree of confidence and certainty. For that, it is necessary to

(1) Have extensive site-specific geophysical and geotechnical investigation data including sufficient in-situ (such as cone penetration tests) and laboratory (e.g., triaxial, direct simple

shear) test data. Laboratory test data on remoulded soils are also useful to assess soil sensitivity and to evaluate the effect of sample disturbance on laboratory test data.

(2) Assess site investigation data and extract design soil strength profiles carefully. This includes identification of layer boundaries, and soil type and design strength parameters (including upper and lower bound values) for each identified layer.

(3) Calculate spudcan load penetration profiles precisely using appropriate calculation methods or approaches.

As data uncertainty increases due to limited experience in the location or site, limited site investigation data, and quality of data and/or provided information; a higher factor of safety should be considered. In addition, this method does not consider geohazards such as buried channels, spudcan footprints, uneven seafloor, boulders, or development of an artificial thin strong layer beneath a spudcan due to a halt during preloading and consequent consolidation that has taken place. Additionally, it does not consider dynamic loads that may change the stress state by altering soil in-situ pore pressures.

Another important cautionary note is that a result of "high-risk" of punch-through based on the modified chart for a given jack-up should not be the sole basis for rejecting such jack-up. Additional analyses (e.g., using upper and lower bound soil parameters for each of the soil layers in various combinations), special preloading measures (e.g., preloading one leg at a time) and mitigative approaches (e.g., seabed soil modifications) should be considered before rejecting the jack-up. Further cautions, guidance, and mitigative measures can be found in ISO 19905-4 (ISO, 2022).

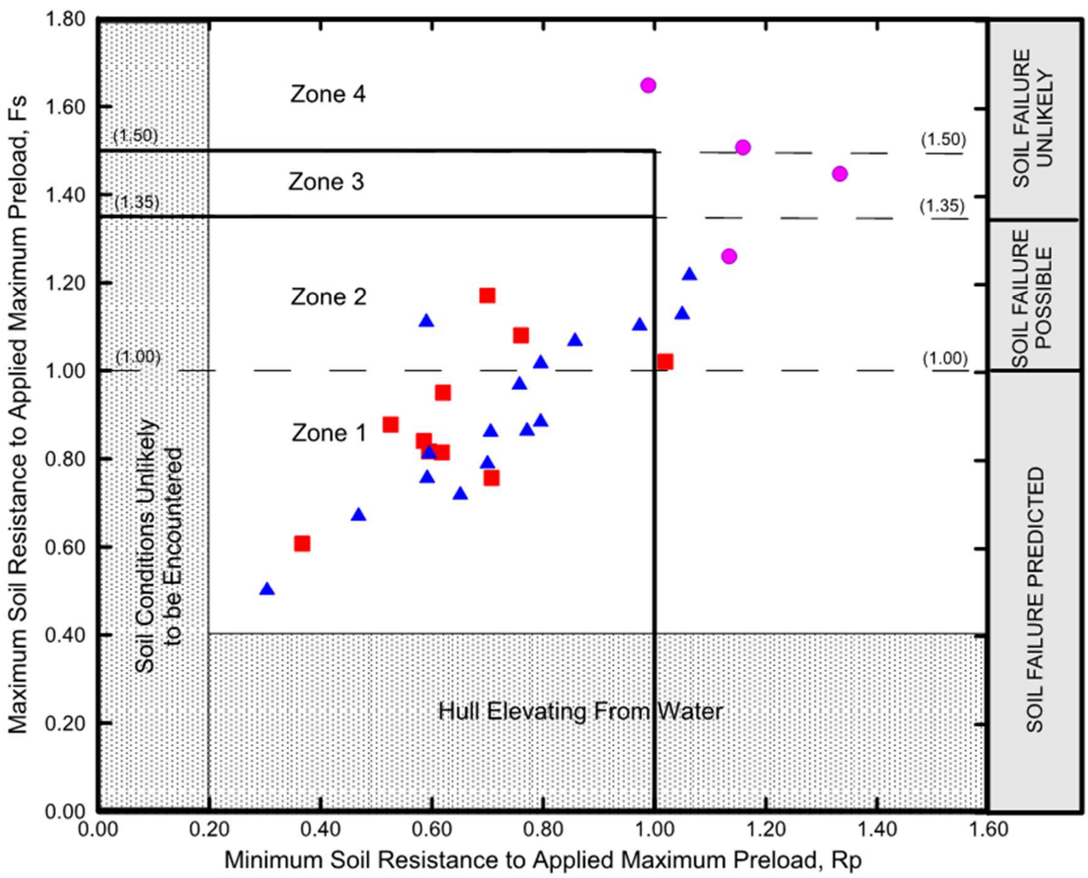


Figure 7. Performance of modified factor of safety design chart against 29 case histories collected from different locations around the world

CONCLUDING REMARKS

This paper has proposed a modified factor of safety design chart for assessing potential of spudcan punch-through failure during installation and preloading of independent-legged mobile oil and gas drilling jack-up rigs and wind turbine installation vessels in seabed sediments where a strong layer overlays a weaker layer. The chart has been plotted on Fs - Rp space where Fs = Q_{max} / V_{Lo} (maximum geotechnical bearing capacity of the strong layer/designed maximum preload to be applied); (ii) Rp = Q_{min} (minimum bearing capacity of the weak layer)/ V_{Lo}. Possible load penetration curves in strong over weak soil layers have been plotted for visualising the cases, and based on those cases the failure envelopes and boundaries of Fs and Rp axes were modified relative to the ones proposed by McClelland Engineers (1983) and Senner (1993). This paper has also reported 29 case histories collected from different locations around the world. The performance of the proposed modified design chart in estimating the likelihood of punch-through has been assessed against those 29 case history datasets. It was reasonably confirmed that the modified chart can be used in practice for evaluating the potential of punch-through failure. Uncertainties and cautions have been highlighted.

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