

Effect of Pore Water Pressure Ratio on Stability of Wind Turbine Shallow Foundations on Saturated Sandy Soil Due to Soil Liquefaction: A Case Study in Coastal Area of Soc Trang Province, Vietnam

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Abstract

Wind turbines are structures whose operation is always affected by dynamic loads. Currently, shallow foundations are common for onshore wind turbines. In the case of saturated sandy soils, dynamic stresses caused by wind turbines can cause the sand to liquefy or reduce its shear strength due to increased excess pore water pressure (ΔU). The pore water pressure ratio ($R_u = \Delta U/\sigma'$) is now often used to evaluate the effect of ΔU on foundation stability. This paper presents a method for determining R_u and establishing equations to determine the shear strength of saturated sand from R_u . From there, it is possible to estimate the bearing capacity of the foundation on saturated sand (q'_{ult}), taking into account the effect of the pore water pressure ratio. Using the concept of influence factor of liquefaction (F_{inf}), this paper proposes a procedure to evaluate the effect of pore water pressure ratio on the stability factor of shallow foundations on saturated sandy soil. Applying the above method to the coastal area of Soc Trang province, Vietnam shows that the values of q'_{ult} and R_u are inverse exponential relationships while F_{inf} and R_u are exponential relationships. In particular, q'_{ult} and F_{inf} have a very close correlation with R_u and can be expressed as the following expression: $F_{inf} = 0.9907e^{3.56R_u}$; $q'_{ult} = 44450e^{-3.56R_u}$.

Keywords: Bearing capacity; Liquefaction; Pore water pressure ratio; Stability; Soc Trang province.

1. Introduction

Saturated sandy soils are susceptible to liquefaction under dynamic loading due to the creation of excess pore water pressure (Dobry et al., 1980; Ishihara, 2003). The liquefaction properties of sandy soils depend on factors such as soil particles, soil density, stress state in the field, and characteristics of dynamic loading (Ishihara, 2003; Vijay and Shamsheer, 2013). The soil liquefaction can occur at different rates depending on the pore water pressure ratio (R_u), which is the relationship between excess pore water pressure and vertical effective stress ($R_u = \Delta U/\sigma'$). Liquefaction will reduce the bearing capacity and affect the long-term stability of the foundation or can cause serious damage to construction projects, especially when there is an earthquake. Therefore, it is very important to evaluate and predict the stability or bearing capacity of foundations on saturated sandy soils due to soil liquefaction under dynamic loading.

Nowadays there have been many studies on the liquefaction potential of soils (Robertson and Fear, 1995; Beaty and Byrne, 1998; Liu et al., 2001) and the increase in excess pore water pressure in saturated

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sandy soils (Marcuson and Haynes, 1990; Chiaradonna et. al., 2018; Chiaradonna et. al., 2019). Several studies evaluated the reduction in soil shear strength due to excess pore water pressure and its effect on soil bearing capacity (Al-Karni, 2001; Vijay and Shamsheer, 2013; Lu-Qing and Li-Zhong, 2015). Alaatabi et al. (2022) determined soil bearing capacity using cross-hole seismic survey for a water treatment plant, Thi Qar, Southern Iraq. Eissa (2022) studied the identification of different shallow foundations using 3D electrical resistivity modeling. In Vietnam, there have recently been a number of studies on the possibility of sand liquefaction (Binh, 2014; Phong, 2015), which mainly evaluated the possibility of sand liquefaction due to earthquakes. Phan and Huy (2016) evaluated the bearing capacity of the liquefied sand layer under the raft foundation. Phong (2020) studied the dynamic shear strength and liquefaction properties of sand in the coastal area of Soc Trang and evaluated the influence of pore water pressure ratio on the bearing capacity of wind turbine pile foundations.

Recently, renewable energy in general and wind power in particular have developed strongly in many countries, including Vietnam. Vietnam boasts a 3260 km coastline and is located close to the equator, making it a prime location for solar and wind energy. With more than 39% of the total area estimated to have an average annual wind speed greater than 6 m/s at an altitude of 65 m, Vietnam is one of the four countries in the region with the largest wind potential. This is equivalent to a total capacity of 512 GW (Decision No. 3909/QĐ-BCT of the Ministry of Industry and Trade, 2014). Therefore, wind power is being encouraged by the Vietnamese Government. Wind farms are often built on the coast or offshore, where sandy soil is often present. Wind turbine operation is always affected by dynamic loads such as wind, waves, earthquakes, and rotation of the rotor. Under these dynamic loads, excess pore water pressure in sandy soils can gradually increase, causing the soil's shear strength to decrease, or more dangerously, to liquefy. Common foundation types for onshore wind turbines are shallow foundations or spread foundations. In general, evaluating the stability of shallow foundations for wind turbines is quite complicated, including bearing capacity, anti-overturning stability and anti-sliding stability. In Vietnam, studies on liquefaction and bearing capacity of liquefied soil have been conducted as mentioned above. However, the method for determining R_u has not yet been systematically elucidated. In addition, there have been no studies on the stability or bearing capacity of shallow foundations for wind power turbines on saturated sandy soil due to soil liquefaction.

The content of the article presents the theoretical basis, method for determining R_u and establishing equations to determine the shear strength of saturated sand from R_u . From there, it is possible to estimate the bearing capacity of the foundation on saturated sand, taking into account the effect of pore water pressure ratio. Using the concept of influence factor of liquefaction (F_{inf}), this paper proposes a procedure to evaluate the effect of pore water pressure ratio on the stability factor of shallow foundations on saturated sandy soil due to soil liquefaction. Apply the above method to coastal area of Soc Trang province, Vietnam.

2. Theoretical Basic and Method

To evaluate the effect of pore water pressure ratio on the stability factor of shallow foundations on saturated sandy soil due to soil liquefaction, it is necessary to present some parameters and coefficients as follows:

2.1. Stability Coefficient of Sand Under Dynamic Loading, I_d

In the case of saturated sandy soils, cyclic stress causes excess pore water pressure (ΔU) and reduces effective stress (σ') leading to a decrease in the shear strength of the soil which is directly related to the pore water pressure ratio ($R_u = \Delta U / \sigma'$). When the dynamic load is strong enough or repeated many times, R_u in saturated sandy soil can increase up to 100%, leading to a reduction of σ' to 0 and the soil loses its shear strength or liquefaction. The increase in R_u over time (the number of cycles)

corresponding to the cyclic stress ratio (CSR) is important information to describe the liquefaction process of sand. This process also differs between types of sand.

An increase in ΔU or R_u leads to a decrease in the shear strength of saturated sandy soil, which can be described based on Coulomb's law as follows:

$$\tau' = \sigma' \tan \varphi = (\sigma - U) \tan \varphi \quad (1)$$

Where: τ' - Shear strength of saturated sandy soil, kPa; σ - Total stress, kPa; U - Pore water pressure, kPa.

When the soil is subjected to dynamic loads, the pore water pressure increases ΔU , leading to a decrease in effective stress. The soil shear strength (τ') is rewritten and expressed in equation 2 (Phong et al., 2020). The decrease in soil shear strength, τ' to τ'_d is shown in Figure 1.

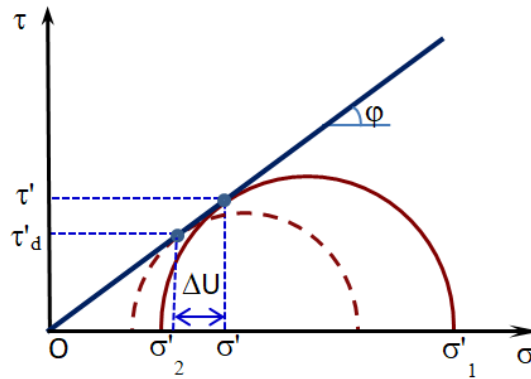


Fig.1. The decrease in soil shear strength, τ' to τ'_d

$$\tau'_d = (\sigma' - \Delta U) \tan \varphi \quad (2)$$

From Eqs. 1 and 2:

$$\frac{\tau'_d}{\tau'} = \frac{(\sigma' - \Delta U) \tan \varphi}{\sigma' \tan \varphi} = 1 - \frac{\Delta U}{\sigma'} = 1 - R_u \quad (3)$$

During cyclic loading, ΔU increases from 0 to σ' or R_u increases from 0 to 1, and τ'_d decreases from τ' to 0. From Eq. 3:

$$I_d = \frac{\tau'_d}{\tau'} = 1 - R_u \quad (4)$$

I_d is called the stability coefficient of sand under dynamic loading (Phong et al., 2020) representing the risk of liquefaction and loss of shear strength of saturated sandy soil. Based on I_d , the shear strength of sand (φ_d) under the effect of dynamic load is determined as follows:

$$\varphi_d = \arctan(I_d \tan \varphi) \quad (5)$$

The I_d value determines the shear strength of sand used to calculate foundation stability on saturated sand subjected to dynamic loads. This parameter is determined based on Eqs. 4 and Eq 5 when R_u is available.

2.2. Safety Factor Against Liquefaction (F_{SL})

The common method used to evaluate the liquefaction potential is determination of the safety factor against liquefaction (F_{SL}), which is defined as the relationship between the cyclic resistance ratio (CRR) and the cyclic stress ratio (CSR) (Seed and Idriss, 1971):

$$F_{SL} = CRR / CSR \quad (6)$$

The value of CRR can be estimated based on laboratory tests such as the cyclic triaxial test (ASTM D5311) or on the results of in-situ tests such as standard penetration test (SPT), cone penetration test (CPT) (Seed and Alba, 1986). CSR is the ratio between dynamic shear stress (τ_d) and effective overburden stress (σ'_v):

$$CSR = \frac{\tau_d}{\sigma'_v} \quad (7)$$

The F_{SL} represents the possibility of liquefaction and accumulation of R_u due to earthquake loading in saturated sand. The value of R_u is closely related to F_{SL} . When $F_{SL} \leq 1$, the soil is liquefied and R_u can reach 100%; In case $F_{SL} > 1$, the soil is not liquefied and R_u changes inversely with F_{SL} . Thus, F_{SL} is an important parameter to determine R_u .

2.3. Bearing Capacity of Shallow Foundations for Wind Turbines Under Dynamic Loads And Influence Factor Of Liquefaction, F_{inf}

The bearing capacity (or ultimate load, q_{ult}) of a shallow foundation can be determined using the Terzaghi equation (1943):

$$q_{ult} = c \cdot N_c \cdot s_c + \gamma \cdot D \cdot N_q + 0.5 \cdot \gamma \cdot B \cdot N_\gamma \cdot s_\gamma \quad (8)$$

Where: γ is the bulk density of soil, kN/m^3 ; c is cohesion, kPa ; B , D are the width and depth of the foundation, m ; N_c , N_q , N_γ are coefficients that depend on the internal friction angle of the soil; s_c , s_γ are coefficients that depend on the shape of the foundation, for circular foundation $s_c = 1.3$; $s_\gamma = 0.6$; for square foundation $s_c = 1.3$; $s_\gamma = 0.8$.

The values of N_c , N_q , and N_γ can be determined according to the following equations:

$$N_q = \tan^2 \left(45^\circ + \frac{\varphi}{2} \right) \exp(\pi \tan \varphi) \quad (9)$$

$$N_c = (N_q - 1) \cot \varphi \quad (10)$$

$$N_\gamma = 2(N_q + 1) \tan \varphi \quad (11)$$

In the case of a circular foundation ($s_\gamma = 0.6$) placed on a sand layer ($c = 0$), Eq. 8 can be rewritten:

$$q_{ult} = \gamma \cdot D \cdot N_q + 0.3 \cdot \gamma \cdot B \cdot N_\gamma \quad (12)$$

The risk of liquefaction and loss of soil shear strength should be considered when calculating the stability of shallow foundations for wind turbines. The greater the risk of liquefaction, the smaller the I_d value, leading to a decrease in φ_d and 0 when liquefaction occurs. In this case, the bearing capacity can be estimated based on Eq. 12, but replace φ with φ_d :

$$q_{ult}' = \gamma \cdot D \cdot N_{q'} + 0.3 \cdot \gamma \cdot B \cdot N_{\gamma'} \quad (13)$$

To evaluate the influence of liquefaction on foundation stability, the influence factor of liquefaction (F_{inf}) is proposed:

$$F_{inf} = q_{ult} / q_{ult}' \quad (14)$$

When $R_u \approx 0$, $q_{ult}' \approx q_{ult}$ or $F_{inf} \approx 1$, the value of q_{ult}' decreases as R_u increases. The risk of foundation instability increases as F_{inf} increases.

2.4. Method for Evaluating the Effect Of Pore Water Pressure Ratio on the Stability of Wind Turbine Shallow Foundations

2.4.1. General principles

Under normal conditions without considering R_u , the stability factor (F) is the ratio between the ultimate load (bearing capacity, q_{ult}) and the actual load (q) (Richards et al., 2013):

$$F = q_{ult} / q \quad (15)$$

When a structure built on saturated sand is subjected to dynamic loads, the stability factor taking into account the increase in excess pore water pressure (F') is determined by the following equation:

$$F' = q_{ult}' / q \quad (16)$$

From Eqs. 14, 15, and 16, F' can be expressed as follows:

$$F' = F / F_{inf} \quad (17)$$

Eq. 17 is used to evaluate the stability of foundations on saturated sand under dynamic loading. The structure is stable when the stability factor (F') is greater than the allowable stability factor, $[F]$: $F' \geq [F]$. Thus, if $F_{inf} \leq F/[F]$ then the foundation is stable and vice versa.

In summary, the main content of evaluating the effect of pore water pressure ratio on the stability of wind turbine foundations on saturated sand is to determine F_{inf} .

2.4.2. Material and methods

- Parameters need to be determined

a) Stability factor, F

The stability factor F under normal conditions (not considering the creation of excess pore water pressure under the effect of dynamic loads) is determined according to Eq. 15. In which, the bearing capacity q_{ult} is determined from Eq. 12 based on dimensions of the foundation and soil properties (γ , ϕ). These soil properties can be estimated from the results of SPT. If the depth of the foundation is lower than the groundwater table, the γD value is calculated according to effective stress. The actual load q is calculated based on the dimensions of the foundation and the loads acting on the foundation.

b) Influence factor of liquefaction, F_{inf}

- Determine CSR and τ_d from load acting on the wind turbine foundation. Wind turbines, due to their shape and form (slender column with a heavy mass as well as a rotating mass at the top), have many complex dynamic loads. The main dynamic loads acting on the wind turbine are as follows: wind, waves, 1P load, 3P load, and earthquake (Arany et al., 2015; Subhamoy, 2019);

- Determine CRR directly from cyclic triaxial test or roughly from in-situ test results (Seed and Alba, 1986) and use it to evaluate liquefaction in cyclic triaxial test (ASTM D5311). In which, the stress amplitude is determined from the dynamic load and frequency, $f = 0.4 \div 1\text{Hz}$ (Subhamoy, 2019)

- From the CSR and CRR values determined above, the stability factor against liquefaction F_{SL} is determined according to Eq. 6 and the R_u value obtained from the cyclic triaxial test. The value of F_{SL} can be estimated according to Marcuson and Haynes (1990).

- Use Eq. 4, Eq. 5, and Eq. 13 to calculate I_d , ϕ_d , and q'_{ult} .

c) Determine the stability factor F' according to Eq. 17, thereby evaluating the stability of the foundation.

- Evaluation procedure

Step 1: Collect information about the project's characteristics and technical requirements.

Step 2: Geotechnical investigations to determine input parameters such as.

- Meteorology, hydrology, and earthquake intensity.

- Stratigraphy, composition, physical and mechanical properties of soil.

- In-situ testing includes SPT and CPT.

- Cyclic triaxial test to determine CRR and R_u (ASTM D5311).

Step 3: Preliminary select the foundation dimensions (B , D) and determine q_{ult} according to Eq. 8.

Step 4: Calculate the load acting on the foundation.

- Calculate q from the dimensions of the foundation and the load acting on the foundation, then determine the stability factor F according to Eq. 15.

- Dynamic load includes stress amplitude, frequency and cyclic stress ratio, CSR.

Step 5: Determine CRR from the results of in-situ testing (Seed and Alba, 1986) and cyclic triaxial testing, then calculate F_{SL} according to Eq. 6 and R_u .

Step 6: Use Eqs. 4 and Eq. 5 to calculate ϕ_d and q'_{ult} .

Step 7: Determine the influence factor of liquefaction F_{inf} according to Eq. 14.

Step 8: Determine F' according to Eq. 17 and evaluate the stability based on the allowable stability factor $[F]$.

The diagram of the method to evaluate the effect of excess pore water pressure on the stability of the shallow foundation for wind turbines on saturated sand is shown in Fig.2.

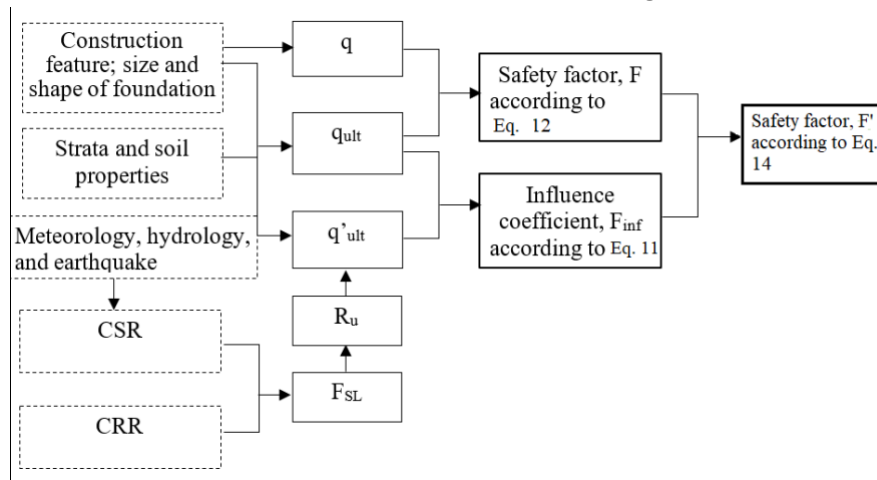


Fig. 2. Diagram to evaluate the effect of R_u on the stability of shallow foundations

3. Test Results and Evaluation Procedures

3.1. Test Results

The coastal area of Vinh Chau town, Soc Trang province, Vietnam (Fig.3) is in the wind power planning area, with a general distribution of sand layers from 5 to 10 m thick. Characteristics of the soil layers in the study area are presented in Table 1. As presented, the sand layers include layers No.1, No.4, and No.5. Layer No.1 is very loose, fine grained sand, over 10 m thick, and has the ability to liquefy.

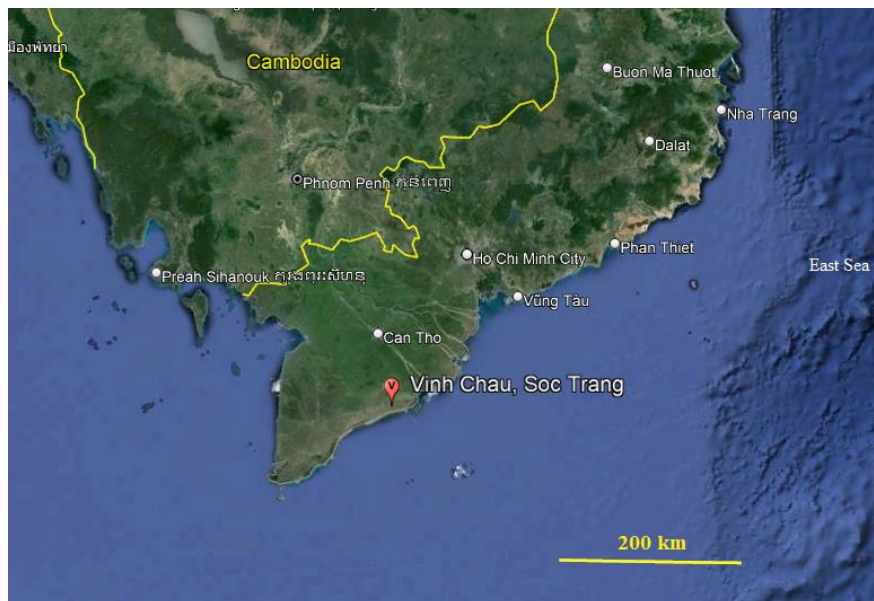


Fig. 3. Location of Vinh Chau town, Soc Trang province, Vietnam (Photo from Google Earth)

Note: N_{SPT} is the total number of blows required to drive the SPT sampler within a depth range of 0.15 to 0.45 m from the bottom of the borehole.

To evaluate the possibility of soil liquefaction, sand samples were taken from layer No.1. Some physical properties of the sand samples are presented in Table 2. The sand layer is poorly graded sand (SP), the grain group content ($0.075 \div 0.106\text{mm}$) accounts for 87%, and the fine grain content is very small.

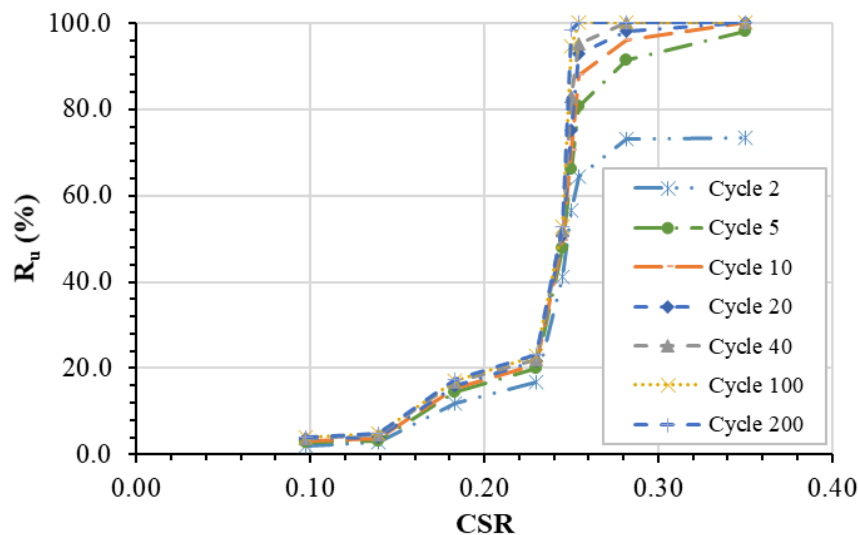
Table 1. Characteristics of the soil layers in the study area (Phong et al., 2022)

Soil layer	Depth (m)		Average thickness (m)	Soil type	N _{SPT} (Blows)
	Layer's top	Layer's bottom			
1	0	9.0-13.0	10.5	Very fine sand, loose state	4-5
2	9.0-13.0	20.0-25.0	13.0	Very soft sandy clay	1
3	20.0-35.0	31.0-35.0	20.0	Soft to firm sandy clay	4-6
4	31.0-45.0	45.5-50.0	8.0	Fine sand, dense state	27-42
5	45.5-50.0	55.0-60.0	10.0	Fine sand, very dense state	>50

The relationship between the increase in pore water pressure (R_u) and CSR is shown in Fig. 4. As shown in this figure, the value of R_u significantly depends on the value of CSR.

Table 2. Some physical properties of tested sand samples

Sand samples	Grain size			Specific density (g/cm ³)	Maximum void ratio	Minimum void ratio
	D ₆₀ (mm)	D ₃₀ (mm)	D ₁₀ (mm)	γ_s	e_{max}	e_{min}
STs	0.189	0.148	0.115	2.65	1.002	0.683

**Fig. 4.** Variation of pore water pressure ratio R_u according to CSR in different cycles (Fine grained Sand - SP, FC<1%, $D_r = 0.549 \pm 0.035$)

3.2. Evaluating the Effect of Excess Pore Water Pressure on the Stability of Shallow Foundations of Wind Turbines on Sandy Soil in the Coastal Area of Soc Trang Province, Vietnam

In the study area, shallow foundations (raft foundations) placed on sand can be used for wind turbines. With this type of foundation, it is necessary to consider the possibility of sand liquefaction affecting the stability of the foundation. In this section, the above method is applied to determine F_{inf} and q_{ult} of the shallow foundations for wind turbines in the study area. The liquefaction ability of this type of sand has been studied by Phong et al. (2022) shows that soil has a high risk of liquefaction. To prevent foundation failure due to liquefaction, a stability factor against liquefaction (F_{SL}) is often used to design the foundation. In this case, although the sand is not liquefied, the pore water pressure still increases significantly, leading to a decrease in foundation stability. Therefore, this section will clarify

the effect of excess pore water pressure on foundation stability by applying the above method to determine F_{inf} according to the F_{SL} .

According to Phong et al. (2022), the increase in R_u under CSR (Fig. 4) shows that value of R_u depends on the choice of F_{SL} . Apply the procedure presented in section 2.4.2 (Fig. 2.) for shallow foundations with dimensions of 3.6m deep ($D=3.6$ m) and 25.6m in wide ($B=25.6$ m) to determine F_{inf} and stability factor F_{inf} . The results are shown in Table 3.

Table 3. Determination of q_{ult} and q'_{ult}

F_{SL}	R_u	I_d	ϕ_d (rad)	N_q'	N_γ'	q'_{ult} (kPa)	F_{inf}	$F=F_{inf} \cdot [F]$ ($[F]=1.30$)
1.10	0.40	0.60	0.333	5.86	4.75	1065.3	4.1	5.38
1.11	0.35	0.65	0.359	6.77	5.83	1280.0	3.4	4.48
1.13	0.3	0.7	0.384	7.83	7.13	1534.8	2.9	3.73
1.20	0.22	0.78	0.423	9.85	9.77	2044.4	2.2	2.80
1.30	0.18	0.82	0.442	11.04	11.40	2355.9	1.9	2.43
1.50	0.14	0.86	0.461	12.38	13.29	2712.3	1.6	2.11
1.70	0.1	0.9	0.479	13.87	15.45	3119.5	1.4	1.84
2.00	0.05	0.95	0.502	15.98	18.63	3711.0	1.2	1.54
2.50	0.04	0.96	0.506	16.44	19.33	3841.4	1.1	1.49
q_{ult}		1.00	0.524	18.40	22.40	4408.5	1.0	1.30

The relationship between R_u and q'_{ult} , and between R_u and F_{inf} is plotted in Fig. 5. As shown in this figure, the values of q'_{ult} and R_u are inverse exponential relationships while F_{inf} and R_u are proportional exponential relationships. In particular, q'_{ult} and F_{inf} have a very close correlation with R_u and can be expressed as the following expression: $F_{inf}=0.9906e^{3.558R_u}$; $q'_{ult}=4450e^{-3.558R_u}$. Based on these correlations, the value of F_{inf} and q'_{ult} can be estimated based on the value of R_u .

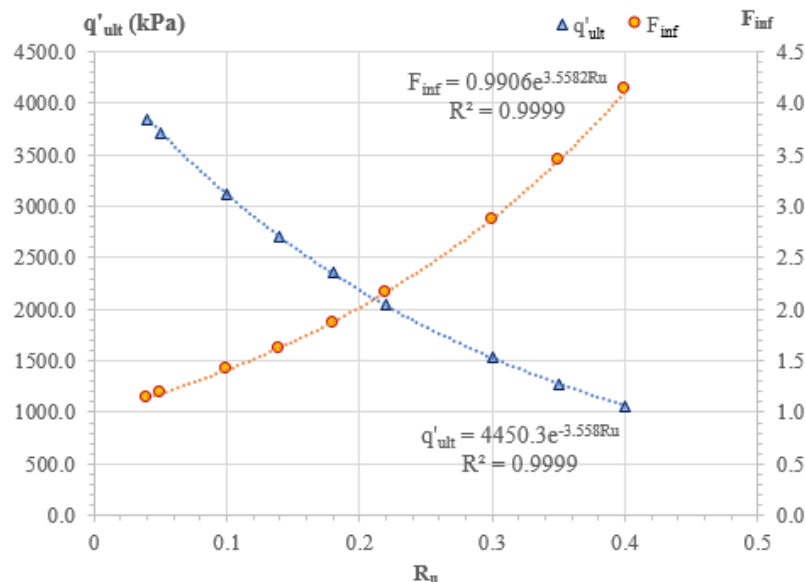


Fig. 5. Relationship between q'_{ult} , F_{inf} and R_u

4. Conclusions

Wind turbine operation creates dynamic loads that cause excess pore water pressure and reduces the bearing capacity of shallow foundations on saturated sandy soils. The pore water pressure ratio R_u is an

important parameter to evaluate the degree of reduction in soil shear strength and foundation stability. This parameter is determined by cyclic triaxial testing with test parameters consistent with the dynamic load combination acting on the wind turbine. The effect of R_u on the stability of the shallow foundation is evaluated by the influence factor of liquefaction F_{inf} . This factor is used to calculate the stability factor F' and the minimum stability factor F for the preliminary design considering the effect of excess pore water pressure. The relationship between q'_{ult} , F_{inf} and R_u is exponential in the R_u range from 0.04 to 0.40.

Applying the above method to the coastal area of Soc Trang province, Vietnam shows that the values of q'_{ult} and R_u are inverse exponential relationships while F_{inf} and R_u are exponential relationships. In particular, q'_{ult} and F_{inf} have a very close correlation with R_u and can be expressed as the following expression: $F_{inf}=0.9906e^{3.558R_u}$; $q'_{ult}=4450e^{-3.558R_u}$.

To improve the reliability of this evaluation method, it is necessary to compare the calculation results with actual monitoring results to adjust input parameters.

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