Influence of degree of saturation in the dynamic stress transmission to a deep foundation

Rafael Baltodano-Goulding[1, 2] *Laura* Brenes-Garcia[1]

[1]LabUnsat, Civil Engineering Department, University of Costa Rica, Costa Rica
[2]Construction Engineering, Costa Rica Institute of Technology, Costa Rica

Abstract. The structural design of deep foundations depends on both the applied loads and the soil that will support them. However, during an earthquake this process reverses, and the seismic stresses are transmitted towards the structure through the soil. Proper design of deep foundations must account for the lateral loads imposed on the foundations by the dynamic loading. In order to assess the influence of soil saturation in the transmission of a dynamic load to a foundation, a dynamic lateral load pile design was performed using Reese's p-y curve method. A series of suction-controlled dynamic triaxial tests were performed to obtain the Modulus of subgrade reaction at different matric suctions and seismic coefficients were back-calculated to perform structural designs. In general terms, it was observed that contemplating a saturated soil in the dynamic lateral load pile design does not represent the critical load case for seismic analysis.

1 Introduction

Under static conditions, a foundation is the structural element in charge of the transmission of the loads towards the soil. Thus, the structural design depends on both the applied loads and the soil that will support them. However, during an earthquake this process reverses, and the seismic stresses are transmitted towards the structure through the soil. Proper design of deep foundations must account for the lateral loads imposed on the foundations by the dynamics loading. The transmission stress efficiency is a function of the soil's state of effective stresses, and its stiffness, and these soil properties are a function of the matric suction that changes with the degree of saturation. Therefore, it is imperative that the soil's dynamic behavior and the foundation response be understood during an earthquake to prevent or mitigate the damage that a structure can experience.

Some previous research has been conducted on the subject of lateral loading of pile foundations. Gonzalez [1] determined that design methodologies such as Matlock & Reese, and Winkler do not produce reliable results when compared to Finite Element Modeling, and recommends that they ought not to be used for the final design. Moreover, Mokwa et al [2] developed p-y curves for unsaturated silts and clays. In regards to Suction-controlled cyclic triaxial testing, Suprunenko [3] studied the effect of soil suction on the increase of the Dynamic Shear Modulus of unsaturated sands.

One of the most used methodologies to assess the lateral load capacity of deep foundations is Reese's p-y Method [4], but this approach only considers conditions where the soil is fully saturated or completely dry. It is commonly assumed that saturated conditions will represent the most critical conditions because it is at this degree of saturation where the soil will exhibit its lowest state of stress and stiffness, thus providing conservative estimates of the lateral load capacity of the soil and the foundation. it's considered as the critical design condition as it presents the lowest soil strength, when it's not necessarily so. Nevertheless, in a seismic condition where the direction of the stress transmission reverses, the unsaturated condition of the soil will transmit more energy to the structure due to its greater state of stress and efficiency of stress transmission; consequently, considering the soil as saturated under seismic loading will produce an underestimation of the energy transmitted to the structure and its dynamic behavior.

It could be argued that the critical design condition for a structure subjected to dynamic loading is not when the soil suction equals zero, but at an unsaturated condition. It should be borne in mind that the velocity wave propagation (V) in any material depends on its stiffness, which is represented by the secant modulus (G) and density (ρ), as shown in equation 1.

$$G = \rho V^2 \qquad (1)$$

It is worth mentioning that the values of these two factors are a function of the soil water content, indicating that the magnitude of the dynamic load that will reach the structure depends on the soil saturation. Consequently, the dynamic load that affects the structure is not only a function of the seismic characteristics but also of the soil

* Corresponding author: rafael.baltodanogoulding@ucr.ac.cr

dynamics properties that change with the moisture changes that occur in the soil, and this should be accounted for in the structural foundation design and dynamic behavior of the structure.

2 Material used

The disturbed soil sample used for this paper was obtained from the Central Valley of Costa Rica, Central America. No undisturbed samples were obtained since it was decided to test remolded soil specimens, in order to reproduce identical specimens in the laboratory, and better controlled the density variable. The results from the soil's characterization are shown in

Table **1**. For the shear strength test, the soil specimen was remolded considering the Proctor's Standard Compaction test results.

Table 1. Soil Sample Characterization. [5]

Laboratory test	Index property	Value
Specific gravity	Specific gravity	2.68
Grain size analysis	Percentage retained sieve #4	8.29%
	Percentage passing sieve #200	52.84%
Atterberg limits	Liquid limit	49
	Plastic limit	35
	Plasticity index	14
Soil classification system	USCS	Sandy silt (ML)
	AASHTO	A – 7 – 5 (6)
Proctor standard compaction	Maximum dry density (g/cm^3)	1.432
	Optimal water content	29.45%
UU triaxial test	Total unit weight (g/cm^3)	1.846
	Final water content	29.9%
	Undrained shear strength (kg/cm^2)	3.95 (387.4 kPa) (8.1ksf)

3 Methodology

In order to assess the influence of soil saturation in the transmission of a dynamic load to a foundation, a dynamic lateral load pile design was performed using Reese's p-y curve method. This design method considers the soil stiffness with the relative stiffness factor (T), which relates Young's modulus and the moment of inertia (EI) with the rate of increase of soil modulus with depth coefficient (n_h), as presented in Equation 2

$$T = \left(\frac{EI}{n_h}\right)^{1/5} \tag{2}$$

The rate of increase of soil modulus with depth coefficient can be obtained with the ratio between the soil modulus (E_s) and the depth (z), shown in Equation 3:

$$n_h = \frac{E_s}{z} \tag{3}$$

The soil's Modulus of Subgrade Reaction (E_S) is the relationship between the soil resistance to a lateral load (p) and the lateral deformation (y), like Equation 4:

$$E_s = \frac{p}{y} \tag{4}$$

The soil's Modulus of Subgrade Reaction is the slope of the p – y curve, which arises from the theory of the subgrade reaction, where the lateral loads are represented by springs at different pile locations to avoid establishing a linear elasticity of the soil [4]. At different depths, there will be different soil reactions, so there will be different p – y curves. However, it's common to consider the same value of the Modulus of Subgrade Reaction at any depth when fine-grained soils are analyzed.

Experimental Moduli of subgrade reaction were determined considering different degrees of saturation, and they were utilized to perform lateral pile capacity analyses by Reese's methodology, instead of the proposed saturated Modulus of subgrade reaction. Analyses using the recommended values of Moduli of Subgrade reactions were also performed, and then compared to the results obtained using experimental values. Employing this comparison, it is possible to compare the seismic coefficient used for structural design and evaluate the influence of water content changes in the soil in the structural design.

The seismic coefficient used for this research was obtained from Costa Rica's Seismic Code (2014) [6], which is selected based on historical seismic behavior and type of soil, but assumes that the soil is fully saturated. With the seismic coefficient, the dynamic load can be determined based on the pseudostatic method established in this Code, which consists of an equation that relates the seismic coefficient with the structure's weight to obtain the basal shear force.

Theoretical Moduli of subgrade reaction for clay were used according to the Manual of pile design and construction by the Federal Highway Administration (FHWA) of the U.S. Transport Department [5], shown in Table 2.

Table 2. Representative Modulus of Subgrade Reaction Values, for Clays. [7]

Soil type	Avg. Undrained Shear Strength (ksf)	Modulus of Subgrade Reaction (pci)	
		Static Loading	Cyclic Loading
Soft Clay	0.25 – 0.50	30	-
Medium Clay	0.50 – 1.0	100	-
Stiff Clay	1.0 – 2.0	500	200
Very Stiff Clay	2.0 – 4.0	1000	400
Hard Clay	4.0 – 8.0	2000	1000

The failure criterion of pile design in Costa Rica's Foundation Code establishes a pile's maximum lateral deformation that must be less than or equal to 10% of the pile diameter [6].

A series of three dynamic suction-controlled triaxial tests were performed in order to obtain the experimental Moduli of subgrade reactions at degrees of saturation that represent unsaturated conditions. The same failure criterion was used during laboratory testing. All three soil specimens were tested with the same density and equilibrated at different matric suctions. For this particular case three different degrees of saturation were tested: the fully-saturated condition, and two unsaturated conditions that are representative of field conditions for the location of the project used to obtain information for the structural design. From a theoretical standpoint, it is desirable to test a wider range of suctions, so different values would be used in future research efforts. In Table 3 the soil properties of the specimens are summarized.

Table 3. Soil Properties of the Dynamic Suction-Controlled Triaxial Test Specimens. [5]

Specimen	1	2	3
Total unit weight (kN/m^3)	18.191	18.152	18.172
Molding moisture	29.06%	29.06%	29.18%
Associated suction (kPa)	0 (saturated)	46	134

From the dynamic triaxial tests, axial hysteretic cycles were obtained for the deviator stress as a function of axial strain in the soil specimen. According to the Federal Highway Administration (FHWA) (2016) [7], the soil Modulus of subgrade reaction is equal to the secant modulus for Reese's p – y curve methodology. By associating the deviator stress due to soil strength with the axial strain associated with lateral soil deformation, the soil modulus of subgrade reaction can be obtained from the cyclic secant modulus of the axial hysteretic cycle. Once the Modulus of subgrade reaction is obtained from testing, it is possible to obtain the soil modulus with depth coefficient for a particular pile depth. For this coefficient to be applied in any pile design a unit length of one was considered. Consequently, the Modulus of subgrade reaction and the cyclic secant modulus will have the same numerical value, but different units.

To obtain the cyclic secant modulus, the results of one loading cycle were considered using the axial hysteretic cycle and the slope between the origin of the hysteretic cycle and its amplitude, as shown in Fig. 1 as an example. It's important to mention that only six cycles from each specimen were chosen due to the high number of cycles that were tested.

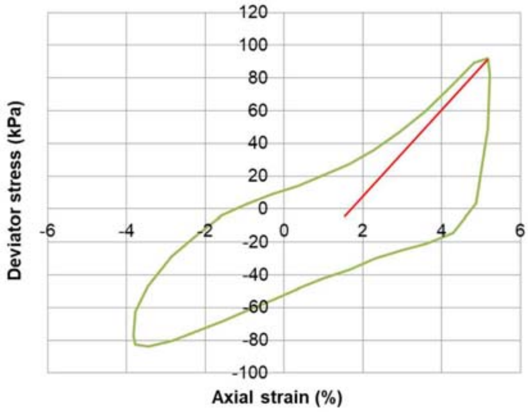

Fig. 1. Secant Modulus from Load Cycle #75 of the Saturated Specimen. [5]

With these experimental results and using the maximum lateral deformation (δ_{max}) obtained from the dynamic lateral load pile design with the theoretical parameters of soil stiffness, the lateral load (P) associated with each experimental Modulus of subgrade reaction can be obtained with the equation below:

$$P = \frac{\delta_{max} EI}{T^3 A_\delta} \tag{5}$$

Where A_δ is equal to 2.435, because it is associated with the depth where the maximum lateral deformation is calculated. This lateral load represents the seismic load that the foundation transmits to the structure. Therefore, to obtain the seismic coefficient (C) for each experimental subgrade modulus coefficient, the following equation is used:

$$C = \frac{P}{W} \tag{6}$$

Where W is the structure weight, which is a constant. Comparing these results, it is possible to assess the effect of the changes in the degree of saturation of the soil on the actual seismic coefficient. Further discussion of the effect of degree of saturation on the soil dynamic properties is discussed by the authors in a different paper.

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4 Results and analysis

Table 4 displays the results obtained from the dynamic lateral load pile design with Reese's p-y curve method considering the theoretical parameters. For this analysis, a pile diameter of 50 cm was used and the lateral load failure criterion is met at a maximum lateral deformation value of 4.31 cm. According to the Costa Rican Seismic Code, this type of soil corresponds to an S3 soil type, and a global ductility of 1 and the dynamic spectral factor of 2.5 was considered. For the theoretical Modulus of subgrade reaction, a value associated with a soft to moderate stiff clay was used.

Table 4. Dynamic Lateral Load Pile Design with Theoretical Parameters. [5]

Parameter	Value
Seismic coefficient (C)	0.75
Considered structure weight (tonne)	82.85
Lateral load (tonne)	62.00
Pile diameter (cm)	50.00
Pile length (m)	10.00
Soil modulus with depth coefficient n_h (tonne/m^3)	1842.75
Relative stiffness factor T (m)	1.38
Maximum lateral deformation δ_{max} (cm)	4.31
Maximum moment M_{max} (tonne-m)	66.03
Maximum shear force V_{max} (tonne)	62.00

Table 5 shows the experimental Soil moduli with depth coefficients obtained from selected load cycles for each specimen tested in the suction-controlled dynamic triaxial test, as well as the seismic coefficients associated with this experimental parameter and the difference between these values and the theoretical seismic coefficient. Fig 2 illustrates the observed behavior of the soil subgrade modulus for the selected load cycles for each specimen tested. As expected as matric suction increases the values of subgrade modulus coefficient and soil stiffness increase, regardless of the cycle number considered. Also, a decrease in the value of the subgrade modulus coefficient can be observed as the load cycles increase, because of a loss of soil stiffness caused by load repetition. Additionally, it is observed that as load cycles increase, the slope of the subgrade modulus softens indicating a loss of soil rigidity related to loading repetition.

Table 5. Seismic Coefficients Associated to Soil Stiffness at Different Degrees of Saturation. [5]

Specimen	Cycle #	n_h (ton/m^3)	C	ΔC
Specimen 1 (saturated)	2	1854.97	0.751	0.002
	25	1574.44	0.681	-0.092
	50	577.77	0.373	-0.502
	75	290.11	0.247	-0.671
	100	166.93	0.177	-0.764
	125	129.20	0.152	-0.797
Specimen 2 (46 kPa suction)	2	7706.11	1.766	1.354
	100	6438.91	1.585	1.114
	200	5082.37	1.375	0.834
	300	3721.77	1.141	0.521
	400	3488.25	1.097	0.463
	499	3053.85	1.013	0.351
Specimen 3 (134 kPa suction)	2	22909.79	3.395	3.527
	100	20082.52	3.137	3.183
	200	19495.68	3.082	3.109
	300	19224.02	3.056	3.074
	400	17986.49	2.936	2.915
	499	17599.10	2.898	2.864

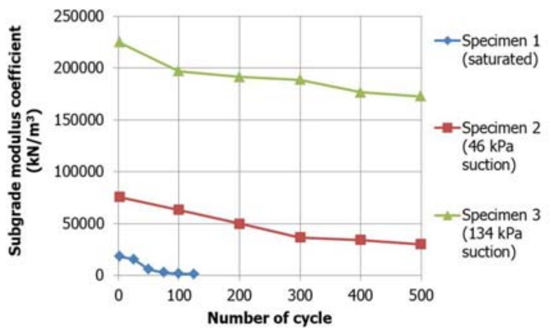

Fig. 2. Subgrade Modulus Coefficient as function of Load Cycles. [5]

As shown in table 5 only specimen 1 exhibits negative differences for the experimental seismic coefficients, with values lower than 0.75, except for cycle 2. For the other two specimens experimentally obtained seismic coefficients are higher than the theoretical values. The largest difference is exhibited for specimen 3 at loading cycle 2, with a value of the seismic coefficient of 3.5.

Fig 3. Shows the subgrade modulus coefficient and the seismic coefficient back-calculated from experimental results for all three specimens tested. The orange dot represents the theoretical pile design condition. The value of the determination coefficient (R^2) of the best-fitted line along the experimental results is 0.999. An increasing trend of the seismic coefficient is observed as the subgrade modulus coefficient increases, which means that the stiffer the soil, the greater the seismic load that the soil will transmit to the foundation, and the foundation to the structure. Thus, the greater the state of effective stress the greater seismic stress transmission towards the structure, and this effective stress could be greatly influenced by the soil degree of saturation, because of changes in matric suction.

On the other hand, it was observed from the experimental results that if the soil is subjected to several load cycles, then its stiffness will decrease. It was observed that for specimen 1 the results for load cycle 2 are the same as for the saturated condition, which is expected; but as load cycles increase, the stiffness of the soil decreases. It is worth mentioning, that the theoretical modulus of subgrade reaction Reese´s method presents corresponds to a static condition since no dynamic values are presented for unsaturated conditions. In addition, the growth of the seismic coefficient back-calculated suggests that taken a saturated theoretical point, does not necessarily predict the maximum possible seismic load transmitted to a structure. This tendency occurs because the degree of saturation of the soil not only affects soil shear strength, but also the soil-structure interaction and the acceleration of the structure produce by the transmitted seismic wave.

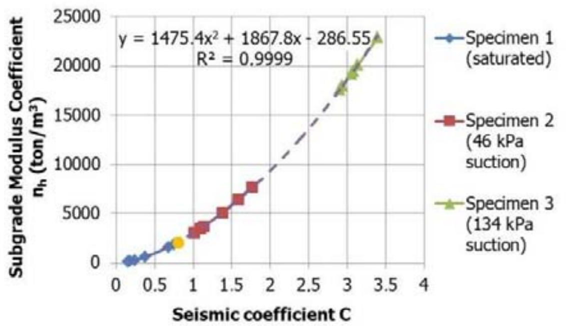

Fig. 3. Subgrade Modulus Coefficient in Function of the Seismic Coefficient. [5]

Finally, in order to compare the influence of the findings of this research in the structural design of piles subjected to lateral load two different design were performed: one using the theoretical Reese´s method, established by the FWHA (Table 2), and another one using the experimental values obtained. It is worth mentioning that further research must be performed in order to account for the influence of the assumption made related to selecting the seismic coefficients and theoretical values of soil stiffness in the results used to analyze the behavior of soil stiffness in the dynamic lateral load pile design.

The pile design using theoretical values is presented in Fig. 4, while Fig. 5 shows a pile design considering the results associated with cycle #2 from specimen 3 (134 kPa matric suction). It was determined that the pile design from specimen 3 requires the double of the diameter as compared to the design using theoretical saturated values, and the amount of steel required is much higher. This is due to the fact that, as there was a considerable increase in the seismic coefficient for the unsaturated specimens, so there is a greater lateral load transmitted to the foundation, producing an increase in the moment enough to surpass the minimum diameter obtained for the saturated condition. In general terms, it was observed that contemplating a saturated soil in the dynamic lateral load pile design does not represent the critical load case for seismic analysis.

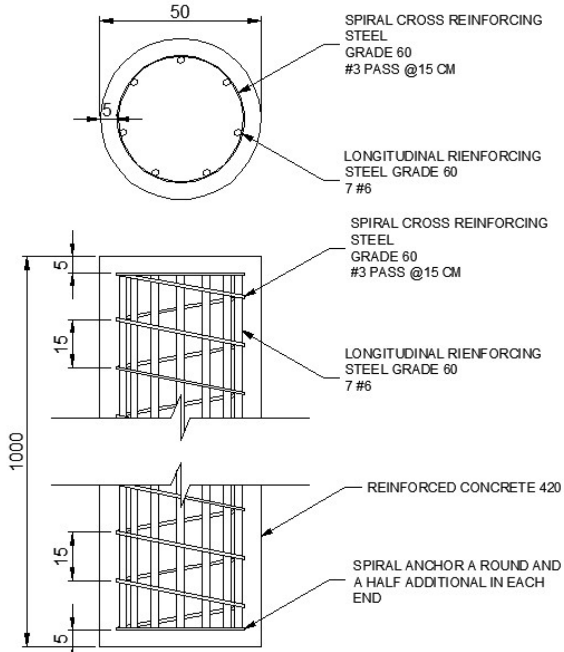

Fig. 4. Pile Design With Theoretical Parameters. [1]

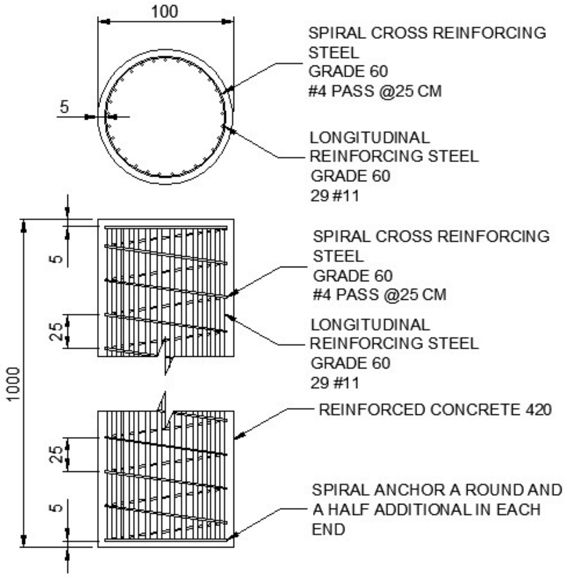

Fig. 5. Pile Design With Experimental Parameters (Specimen With 134 kPa Suction). [5]

5 Conclusions

The subgrade modulus coefficient of soil can be obtained experimentally by means of a cyclic triaxial test. The soil modulus, which is represented by the slope of the p – y curves, is equal to the elastic secant modulus of the axial hysteretic cycle obtained in the cyclic triaxial test. The subgrade modulus coefficient is equal to the soil modulus times the pile length. In order to apply this value for different piles, a unit value of length is used. The specimens with the highest suction presented a higher subgrade modulus coefficient than that of the saturated specimen.

There is enough evidence to conduct a more rigorous investigation of the effect of soil's degree of saturation in fine-grained soils on the transmission of seismic loads from the ground towards the foundation, hence, to the structure. The experimental seismic coefficients obtained from the specimens with varying matric suctions showed a difference of up to 3.5 times greater with respect to the theoretical seismic coefficients.

The soil transmits a greater seismic load to the structure if its stiffness is increased, and this factor is directly related to the water content in the soil. This principle is explained with the wave transmission speed equation, which depends on the density and shear modulus of the material, and these values are subject to the water content of the soil.

The results obtained showed that the critical case of a dynamic lateral load pile design cannot necessarily be represented assuming a saturated soil. It was determined that piles with a higher structural requirement may be required in case of unsaturated soil conditions due to the amplification in the transmission of the seismic load from the ground to the structure.

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