Cyclic plate tests on granular soils

Essais cycliques de plaque en sols granulaires

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SYNOPSIS The necessity to get stress-strain parameters of the soil for using them in dynamic analysis, especially in difficult surroundings, in coarse granular soils or when small soil cohesion prevents the extraction of "undisturbed" samples, is compelling to develop in-situ measurement techniques which include the measurements of wave propagation velocities, plate loading tests, and pressuremeter tests applying cyclic stresses. This work presents the results of cyclic plate tests on coarse granular soils carried out for determining the cyclic shear moduli and for getting residual settlement coefficients regarding shallow foundations subjected to cyclic stresses with variable amplitude.

INTRODUCTION

When modelling a soil subjected to cyclic loads, one of the main parameters is the shear modulus, G_c, which becomes smaller as the cyclic shear strain, γ_c, induced by these loads in the soil becomes larger. The function $G_c = G_c(\gamma_c)$ is traditionally determined through laboratory tests or through field tests such as the strong impulse cross-hole method (Troncoso, 1975). During the last decade, field tests have experienced a strong development because in many instances it is very expensive or practically impossible to make laboratory tests on undisturbed samples. One of the tests that is appearing as an alternative to be used instead of the strong impulse cross-hole method is the plate test applying cyclic stresses of constant amplitude and low frequency, around a certain value of the initial static stress (Ortigosa et al, 1981). The method can be used to get the function $G_c(\gamma_c)$ for maximum shear strains under the plate $\gamma_{c\,max} \geq 10^{-2}\%$; for smaller strains it is necessary to use refraction surveys in order to define moduli associated with those strains. However, in most soil-dynamic problems, especially in the zone of the strong motion originated by importat earthquakes, γ_c values are larger than $10^{-2}\%$, so the cyclic plate test can be directly used.

During the last years another problem that has deserved a certain amount of attention is the appraisal of residual settlements of shallow foundations subjected to cyclic stresses. The problem is complex, especially in the case of earthquakes, inasmuch as it requires analyzing soil behaviour under the simultaneous action of waves proceeding from the seismic focus, and of the waves originated due to soil-structure interaction. The problem has been dealt with pure cases of soil-structure interaction (for instance, water waves action on gravity foundations, cyclic loads on foundations for crane bridges, pavements, etc.)wherein residual strains of soil elements are determined using functions obtained through laboratory tests; by introducing these functions into the finite element mesh used in the step-by-step analysis of the problem, the residual movements of the foundation are determined (Marr and Christian, 1981). A similar method has been developed for the case of earthquakes, wherein the problem of soil-structure interaction takes into account solely the initial static stresses induced by the foundation (Chang, 1984). In conclusion, though the problem is conceptually solved, it requires to carry out comparatively sophisticated laboratory tests, with the limitations of securing undisturbed samples.

For pure cases of soil-structure interaction on shallow foundations, with predominance of cyclic vertical loads, it is possible to use cyclic plate tests for obtaining residual settlements. To accomplish this an analogy is established between plate settlements and those that would originate in the foundation. The method affords the advantage of using an in-situ test, though it is limited to cases where the dimensionless frequency of the stress acting on the foundation is smaller that 0.25. This is in order to reproduce the condition of low frequency cyclic load used in the plate tests. This condition is fulfilled in most shallow foundations of conventional civil constructions, implying that the period of the cyclic load must be larger than $25R\sqrt{\rho/G_c}$ where R is the equivalent radius of the foundation and ρ the density of the bearing soil. The analogy has been established for partially saturated granular soils; for saturated granular soils the analogy would apply as long as the liquefaction potential is less than 40% (Maldonado, 1983).

DETERMINATION OF THE CYCLIC SHEAR MODULUS

Figure 1 is a diagram showing the results of a cyclic plate test where ρ_{st}=static settlement of the plate; σ_{st}= static stress used in the test;

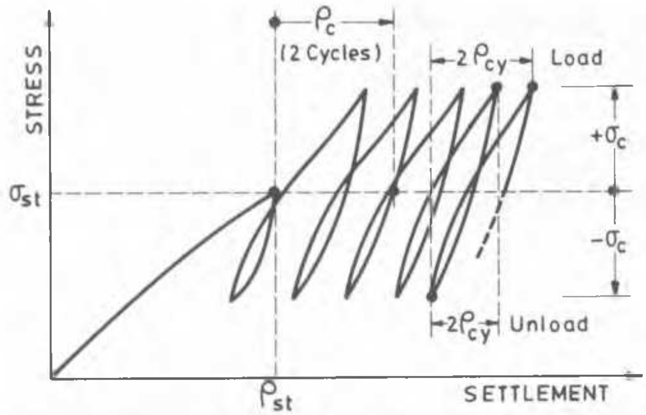

Fig. 1 Scheme of Plate Loading Test Results

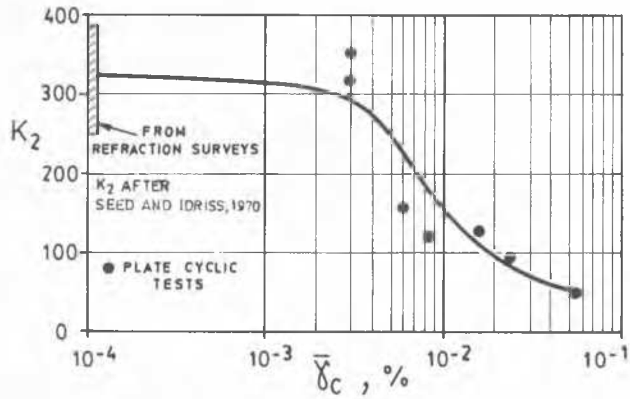

Fig. 3 Cyclic Shear Modulus Coefficient as a function of the Average Shear Strain, Santiago Sandy Gravel deposit

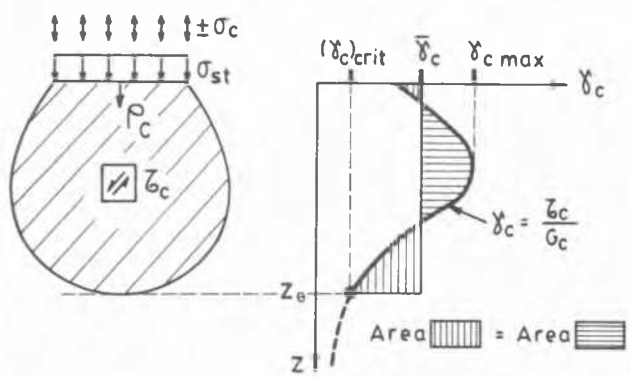

Fig. 2 Cyclic Shear Strain vs Depth under the Center of a Loaded Area

σ_c= applied cyclic stress of constant amplitude; ρ_{cy}= elastic cyclic deformation; and ρ_c= cumulative residual settlement of the plate at the end of N cycles. The maximum cyclic shear stress, τ_c, induced under the center of a rigid circular plate of radius R (type of plate normally used in the tests) can be expressed through relations based on the theory of elasticity as $\tau_c = \sigma_c f(\nu, R/z)$ where z represents the depth under the center of the plate and ν the Poisson ratio of the soil. The cyclic shear strain at this depth is expressed as $\gamma_c = \tau_c/G_c$. On the other hand, considering a typical value of $\nu = 0.30$ and using the relation for the settlement of a rigid circular plate resting on an elastic half space, the following relation is established:

$$G_c = 0.55\ R\ \frac{\sigma_c}{\rho_{cy}} \qquad (1)$$

By combining the above expressions we get:

$$\gamma_c = 1.82\ f(0.30, \frac{R}{z})\ \frac{\rho_{cy}}{R} \qquad (2)$$

For $\nu = 0.30$ the function f(R/z) reaches a maximum value of 0.325 so that:

$$\gamma_{c\,max} = 0.59\ \frac{\rho_{cy}}{R} \qquad (3)$$

Figure 2 is a diagram showing the variation of γ_c as a function of z, where it is defined a limit depth, z_e. Within $0<Z<Z_e$ major cyclic shear strains are induced and hence the major contribution to cyclic deformation ρ_{cy} is obtained. For practical purposes it is possible to adopt $z_e = 4R$ and by doing this to define the average cyclic shear strain under the center of the plate, $\bar{\gamma}_c$. Using the criterion of equal areas defined in Fig.2 we get $\bar{\gamma}_c = 0.5\ \gamma_{cmax}$.

In Fig. 3 the classical coefficient K_2 has been plotted as a function of the cyclic shear strain, where K_2 relates the cyclic shear modulus G_c with the equivalent isotropic stress σ'_o. Values of σ'_o were computed at $z \approx R$ when the static stress was acting on the plate-soil contact. The K_2 coefficient was obtained by using the classical relation $G_c = 219\ K_2\sqrt{\sigma'_o}$ where σ'_o and G_c are expressed in kPa. On doing this, G_c values were obtained by means of eq. (1) using the average elastic cyclic deformation in loading-unloading for the first 30 cycles. The corresponding value of the cyclic shear strain was the average shear strain $\bar{\gamma}_c = 0.5\ \gamma_{c\,max}$ with $\gamma_{c\,max}$ obtained from eq.(3).

During the test an asymptotic reduction of ρ_{cy} vs N is produced, wherein the first cycle absorbs an important percentage of such reduction, especially when the application of σ_c starts with a loading branch. To minimize this effect it is recommended to start σ_c application in the unloading branch. Even more, the test can be improved by applying ρ_{cy} values of constant amplitude (strain controlled tests) instead of constant σ_c (stress controlled tests). In accordance with eq. (2), the application of constant ρ_{cy} warrants a field of constant amplitude cyclic shear strains while the test is being carried out. However, it must be recognized that this modality requires a more sophisticated equipment.

RESIDUAL SETTLEMENTS DUE TO CYCLIC LOADING

Fundamental equation

In granular soils the residual settlement of a shallow foundation, ρ_c, is originated by volume changes of the skeleton, which in turns are fundamentally originated by the existence of a cyclic shear strain field. According to Dobry et al, 1980, the minimum value of the cyclic shear strain required for producing these volume changes, $(\gamma_c)_{crit}$, is of the order of 10^{-2}%. This allows to determine a z_e that defines a soil volume under the plate or under the foundation, V_c, where $\gamma_c > (\gamma_c)_{crit}$. The average volumetric strain of the densified zone can be expressed as $\bar{\varepsilon}_{vc} = \Delta V_c/V_c$ with $\Delta V_c = K'\Omega\rho_c$ and $V_c = K''\Omega z_e$ where ΔV_c = volume reduction of the densified zone; Ω = area of plate or foundation; K' and K" = constants that depend on the shape of the loaded area. By defining K = K'/K" and using the average cyclic shear strain $\bar{\gamma}_c = p\,\gamma_{c\,max}$ where p is computed by using the criterion set forth in Fig.2, it is possible to get:

$$\frac{\bar{\varepsilon}_{vc}}{\bar{\gamma}_c} = K\,\frac{\rho_c}{z_e}\,\frac{1}{p\,\gamma_{c\,max}} \qquad (4)$$

For a rectangular foundation with a width, 2b, and subjected to a constant amplitude cyclic stress, the maximun shear strain along the vertical foundation axis can be expressed as:

$$\gamma_{c\,max} = \frac{\tau_{c\,max}}{G_c} = \frac{\sigma_c\,f(\nu,\,b/z)_{max}}{G_c} \qquad (5)$$

On the other hand the static settlement of the foundation can be expressed as follows:

$$\rho_{st} = \frac{\sigma_{st}\,(1-\nu)\,b\,I_\rho}{G_{st}} \qquad (6)$$

where G_{st} is the shear modulus of the soil for static loads and I_ρ the classical shape factor that depends on the foundation shape. Considering that $G_c \approx \beta G_{st}$, by combining the preceding relations we get the following expressions, which are valid for constant σ_c:

$$\rho_c = \left(\frac{1}{K}\,\frac{z_e}{b}\,\frac{p}{\beta}\,\frac{f(\nu,b/z)_{max}}{(1-\nu)\,I_\rho}\right)\left(\frac{\bar{\varepsilon}_{vc}}{\bar{\gamma}_c}\right)\sigma_c\,\frac{\rho_{st}}{\sigma_{st}} \qquad (7a)$$

$$\rho_c = (m'_g)\cdot(m'_c)\;\sigma_c\,\frac{\rho_{st}}{\sigma_{st}}\;;\quad m_c = m'_g\cdot m'_c \qquad (7b)$$

The term m'_g depends on ν, on the shape of the loaded area and, to a lesser extend, on σ_c amplitudes. Excepting I_ρ, the remaining terms in m'_g vary slightly with the shape; besides, ν = 0.30 can be considered as a representative value for most granular soils. Hence, from a practical point of view m'_g depends on I_ρ solely. The term $m'_c = \bar{\varepsilon}_{vc}/\bar{\gamma}_c$ represents the compaction function of soil skeleton and it corresponds to a constitutive parameter that increases as the number of stress cycles becomes larger. Therefore, the term m_c defined in eq. (7b) includes geometrical variables and the compaction function of the skeleton. Figure 4 shows the variation of m_c vs N for different granular soils, obtained from cyclic tests on circular plates with R = 0.30 to 0.45 m, $\sigma_{st} = 10^2$ to 10^3 kPa, and σ_c = (0.1 to 0.45)σ_{st}. In this way, knowing $m_c = m_c(N)$ for a particular soil it is possible to determine the residual settlement of a foundation through eq. (7b). In that equation the ratio ρ_{st}/σ_{st} associated with the static load can be obtained by means of the classical relations based on the theory of elasticity. If the m_c function is obtained from circular plate tests, then ρ_c values computed through eq.(7b) must be divided by $1.27 I_\rho$ where I_ρ is the shape factor for the analyzed foundation.

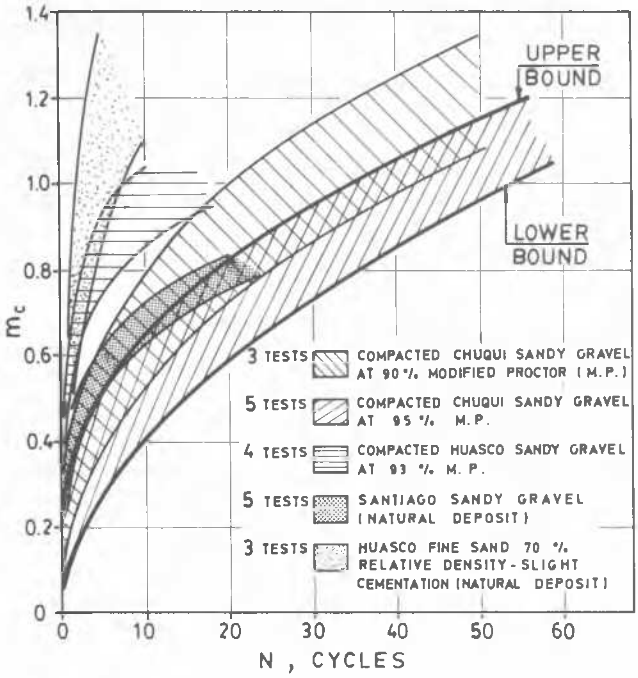

Fig. 4 Residual Settlement Coefficient vs Number of Cycles-Plate Tests with Constant Cyclic stress

<u>Cyclic load with variable amplitudes</u>

From Fig.4 it follows that m_c vs N presents an exponential variation to which a relation of the type $A_c N^B$ can be fitted, where A_c is a constant that depends on the soil type and on the shape of the loaded area while B is a constant that depends on the soil characteristics. By defining A_e as the ratio ρ_{st}/σ_{st} we get $\rho_c = A_o\,\sigma_c\,N^B$ where $A_o = A_c A_e$. Differentiating this last relation and eliminating the term N it follows the relation:

$$d\rho_c = A_o\,\sigma_c\,B N^{B-1} dN \quad \text{with} \quad N = \left(\frac{\rho_c}{A_o\,\sigma_c}\right)^{1/B} \qquad (8)$$

By replacing N in the differential equation and letting dN = 1 cycle we get the increment of the residual settlement, $\Delta\rho_c$, in cycle N+1, which is a function of the residual settlement at the end of N cycles:

$$|\Delta\rho|_{N+1} = A_o^{1/B}\,B\,|\sigma_c|_{N+1}^{1/B}\,|\rho_c|_N^{1-1/B};\quad |\rho_c|_N = \sum_1^N |\Delta\rho_c|_i \qquad (9)$$

By using eq.(9) and taking into account that for the first cycle the value of $\Delta\rho_c$ is equal to $A_o|\sigma_c|_{N=1}$ it is possible to obtain the evolution of ρ_c vs N for a σ_c history with variable amplitude. When these equations are applied to the case of a particular foundation, if the m_c used is obtained through tests on circular plates, the A_c constant resulting from the fitting procedure must be divided by $1.27 I_\rho$. Figure 5 shows a comparison between the results obtained using eq.(9) and the results directly obtained

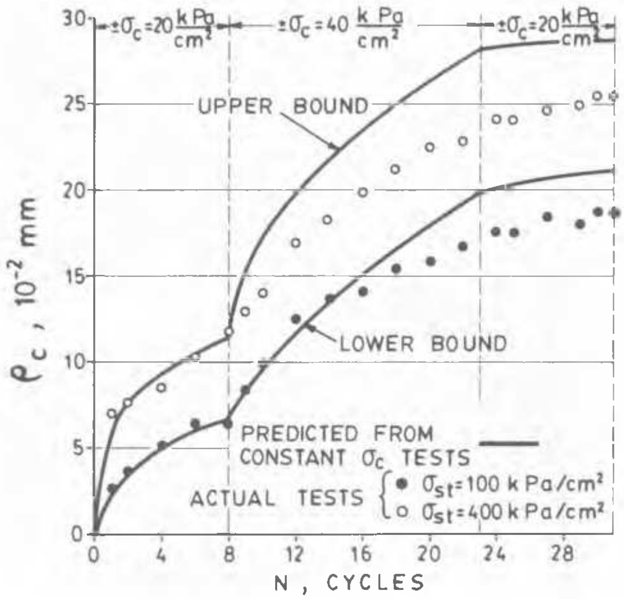

Fig. 5 Residual Cyclic Settlement on Compacted Chuqui Sandy Gravel at 95% M.P. Plate Tests 60 cm diameter

from plate tests with variable cyclic stress application. The tests were made on a fill denominated Chuqui sandy gravel compacted at 95% MP where results from constant σ_c plate tests were available (Fig. 4). By means of these constant σ_c tests it was possible to define the A_c , B and A_e constants present in the computational model. The results are satisfactory, especially if taking into account soil variations among the different points of the compacted fill on which the plate tests were performed.

CONCLUSIONS

Cyclic plate tests are appearing as an alternative approach for defining soil rigidity as a function of cyclic shear strains. Though they present the problem of inducing non-uniform cyclic strains under the plate, it is possible to define an average cyclic strain which can be related to the respective cyclic shear moduli. The test can be improved by controlling the cyclic displacement amplitude, although this modality requires a more sophisticated equipment.

Cyclic plate tests covers the computation of residual settlements on shallow foundation subjected to predominantly vertical cyclic stresses with variable amplitudes. The application is limited to granular soils and to pure soil-structure interaction problems with a dimensionless frequency less than 0.25. However, within these established limits such tests represent a useful alternative when laboratory test implementation on undisturbed samples is practically impossible. Even more, the use of such tests could be useful for the appraisal of in-situ soil compactation functions by resorting to controlled-cyclic-amplitude tests.

ACKNOWLEDGMENTS

The authors acknowledge the use of valuable field data provided by CODELCO Chile, Chuquicamata Division; grateful appreciation is due to the Civil Engineering and Construction Departments of the forementioned Division.

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