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The paper was published in the proceedings of the 25th European Young Geotechnical Engineers Conference and was edited by Ernest Olinic and Sanda Manea. The conference was held in Sibiu, Romania 21-24 June 2016.

Settlements of Foundations in Rock Fill due to Cyclic Loading and Creep Effects

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ABSTRACT

Many of the installations and structures at industrial onshore plants are more sensitive than other structures to deformations, differential settlements and rotations of the foundations. The foundations are often supported by a compacted rock-fill. The geotechnical design must therefore determine the displacements and rotations of the foundations on rock-fill under static and cyclic loads (such as loads from machinery, cranes and traffic) and ensure that the displacements are within the limits required for the plant functionality.

This paper presents a method for estimating foundation rotations and settlements due to volumetric and shear strains in the rock-fill down to bedrock. The rock-fill strains include static strains, accumulated cyclic strains and creep strains, developed with time. The theoretical basis of the calculation methods are presented, together with a step-by-step procedure of the analysis. The paper aims to focus on the practical implementation of the procedure in a real industrial project.

Keywords: Rock-fill, settlements, shallow foundations

1. INTRODUCTION

This article presents a method of estimating rotations and settlements for rigid rectangular foundations on rock-fill over bedrock. A step-by-step procedure of the complete analysis is presented together with the theoretical basis of the implemented calculation methods. An example analysis is presented at the end of the paper.

The calculation procedure was developed in connection with an industrial project with strict requirements to foundation rotations and settlements because of deformation sensitive installations. The industrial project consisted of a large factory hall with dimensions of approximately 80 x 200 metres with a great number of foundations supporting the main construction and various installations. The strict requirements were connected to differential settlements between certain foundations supporting the same installations. Knowledge of the ground conditions were limited, but old site investigations indicated that there could be expected to be up to approximately 2.5 meters of from bottom of foundation level to bedrock. The fill material was assumed to be well-graded and compacted crushed rock.

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2. STEP-BY-STEP PROCEDURE

The procedure for analysis of settlements and rotations of rectangular foundations on rock-fill consists of the following steps:

1. Assess the relative stiffness between the foundation and the rock-fill, Kr (e.g. Selvadurai, 1979).
2. Select the method used to calculate deformations. If the foundation is stiff relative to the rock-fill it is proposed to use the Multiconsult in-house program SPLATE (Athanasiu, 2004). If the foundation is flexible relative to the rock-fill it is proposed to use the Multiconsult in-house program FPLATES (Athanasiu, 1994).
3. Calculate the deformations from permanent loads.
4. Calculate deformations due to cyclic loads (crane passing, traffic etc.).
5. Calculate accumulated cyclic deformations from cyclic loads (e.g. Wichtmann et al, 2010).
6. Calculate creep deformations from permanent loads (e.g. Athanasiu et al., 2005)
7. Calculate the total deformation as the sum of contributions from permanent loads, cyclic loads, accumulated cyclic loading and creep.

3. TEORETICAL BASIS

3.1. Relative foundation stiffness

The relative stiffness of a rectangular foundation can be estimated using the following equations suggested by Selvadurai (1979):

$$K_r = 12 \cdot \pi \cdot \frac{(1-\vartheta_c^2)}{(1-\vartheta_s^2)} \cdot \frac{E_s}{E_c} \cdot \left(\frac{L}{2t}\right)^2 \cdot \left(\frac{B}{2t}\right) \quad \text{(Eq. 1)}$$

In which v_c and v_s are Poisson's ratios for concrete and rock-fill, respectively. E_c and E_s are the elasticity moduli for concrete and rock-fill, respectively. L and B are the dimensions of the rectangular plate (L>B) and t is the thickness of the plate. If Kr is less than:

$$K_{r,lim} = \frac{8}{\sqrt{L/B}} \quad \text{(Eq. 2)}$$

the foundation is stiff relative to the support (rock-fill).

3.2. Calculation of strains in rock-fill

The estimation of rock-fill strains is performed using the Multiconsult in-house program SPLATE or FPLATES, depending on the stiffness of the foundation relative to the rock-fill. This article focuses on analysis of rigid foundations that are relatively stiff compared to the rock-fill, thus the program SPLATE is used. In SPLATE, the plate is assumed infinitely rigid, i.e. the settled position of the plate is a plane defined by three displacements (vertical displacement and two rotations). The ground is modelled as an elasto-plastic half-space. The contact stresses at failure are calculated based on shear strength parameters of the soil. The contact stresses between the plate and the soil are limited to the failure stresses and the excess stresses are redistributed. The input data for SPLATE consists of vertical load and eccentricities about the two axes; x and y in the plate plane. The plate area is divided into a number of discrete elements. The results consists of contact stresses and settlements under each element. The loads are specified about the origin of the coordinate system, which is selected at the corner of the foundation as seen in Figure 1. The vertical load, F_z, acts with the eccentricities, e_x (about y-axis) and e_y (about x-axis). The input eccentricities in SPLATE, e_x and e_y, are defined with respect to the corner of the foundation. The vertical spring stiffness of the foundations are dependent on the elastic properties of the rock-fill, the dimensions of the foundation and on the depth H from the bottom of the foundation plate to the bedrock. As the program SPLATE assumes an elasto-plastic half-space under the foundation, the elasticity modulus entered in the input file of SPLATE must be corrected for the effect of the depth down to bedrock by a factor, f_H:

$$E_{sSP} = E_s \cdot f_H \quad \text{(Eq. 3)}$$

SPLATE calculates both static settlement at the corner of foundation and the rotations. The settlement at the center of foundation δ_{stc} is also printed in the results file.

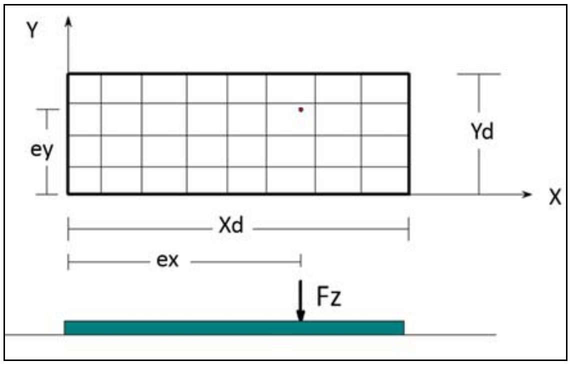

Figure 1. Input data for geometry and loads

3.3. Settlements and rotations due to permanent loads

In the assessment of deformations from permanent loads, all permanent loads are summarized and the resultant force F_{pz}, the resultant moments M_{px} and M_{py} are used in the calculations. The eccentricities relative to the center of the foundation, e_{pxc} and e_{pyc} and the input eccentricities in SPLATE are calculated.

$$e_{pxc} = -\frac{M_{px}}{F_{pz}} \quad \text{(Eq. 4)}$$

$$e_{pyc} = \frac{M_{py}}{F_{pz}} \quad \text{(Eq. 5)}$$

$$e_{px} = e_{pxc} + \frac{X_d}{2} \quad \text{(Eq. 6)}$$

$$e_{py} = e_{pyc} + \frac{X_d}{2} \quad \text{(Eq. 7)}$$

The resultant vertical load and eccentricities are used as input in SPLATE for calculating deformations. The result from this step is the permanent settlement δ_{pz} and rotations θ_{px} and θ_{py}.

3.4. Settlements and rotations due to cyclic and permanent loading

In the assessment of deformation from cyclic loading (crane passing, traffic loads etc.) all cyclic loads are summarized with the permanent loads. The resultant cyclic force F_{cz} and the resultant cyclic moments M_{cx} and M_{cy} are added to the resultant permanent loads:

$$F_{totcycz} = F_{pz} + F_{cyclz} \quad \text{(Eq. 8)}$$

$$M_{totcycx} = M_{px} + M_{cyclx} \quad \text{(Eq. 9)}$$

$$M_{totcycy} = M_{py} + M_{cycly} \quad \text{(Eq. 10)}$$

Calculate the eccentricities relative to the centre of the foundation, $e_{totcycxc}$ and $e_{totcycyc}$ for permanent and cyclic loading and the input eccentricities in SPLATE:

$$e_{totcycxc} = -\frac{M_{totcycx}}{F_{totcycz}} \quad \text{(Eq. 11)}$$

$$e_{totcycyc} = \frac{M_{totcycy}}{F_{totcycz}} \quad \text{(Eq. 12)}$$

$$e_{totcycx} = e_{totcycxc} + \frac{X_d}{2} \quad \text{(Eq. 13)}$$

$$e_{totcycy} = e_{totcycyc} + \frac{X_d}{2} \quad \text{(Eq. 14)}$$

The result from this step is the total cyclic settlement $\delta_{totcycz}$ and rotations $\theta_{totcycx}$ and $\theta_{totcycx.}$ These results are not used directly, only to calculate the settlement from the first cycle loading which is described in section 3.5.

3.5. Accumulated cyclic settlements and rotations

Accumulated cyclic settlements and rotations are additional deformations depending on the number of cycles of the cyclic loading, N. The calculation of accumulated cyclic settlement based on the high cyclic accumulation (HCA) model proposed by Wichtmann et al (2010). The accumulated cyclic settlement and rotations are calculated as:

$$\delta_{acc} = \delta_{cycl1} \cdot (1 + f_N) \quad \text{(Eq. 15)}$$

$$\theta_{acc} = \theta_{cycl1} \cdot (1 + f_N) \quad \text{(Eq. 16)}$$

In which δ_{cycl1} and θ_{cycl1} are settlement and rotations from first cycle of loading, respectively. f_N is the accumulation function, depending on the number of cycles, N:

$$f_N = C_{N1} \cdot [\ln(1 + C_{N2} \cdot N) + C_{N3} \cdot N] \quad \text{(Eq. 17)}$$

C_{N1}, C_{N2} and C_{N3} are material parameters depending on the rock-fill compaction energy, grain size distribution curve and on the coefficient of uniformity, $Cu=d_{60}/d_{10}$. For well-graded gravel (0.05 mm < d < 20 mm) the values of C_{N1}=5.2E-04, C_{N2}=0.03 and C_{N3}=1.3E-05 can be used as conservative estimates to calculate accumulated cyclic settlements.

Settlement and rotation from first cycle of loading (δ_{cycl1} and θ_{cycl1}) are extra deformations occurring during the first cycle of any cyclic load. The first cycle deformations can be calculated using SPLATE (or FPLATES) for the same eccentricities as in total cyclic load analysis ($e_{totcycx}$ and $e_{totcycy}$) but for a load that is very small (i.e. $F_{totcyczo}$=$F_{totcycz}$/10000). The result will be a settlement for the very small load which provides us with the initial unloading/reloading stiffness of the foundation for total cyclic load configuration (eccentricities). The permanent settlement after the first cycle δ_{cycl1} is calculated as the total cyclic settlement $\delta_{totcycz}$ minus the permanent settlement δ_{pz} and minus the elastic (unloading) part (see Figure 2). (Eq. 18) to (Eq. 20) is used for calculation of δ_{cycl1}.

$$\delta_{cyc1}=\delta_{totcycz}-\delta_{pz}-(F_{totcycz}-F_{pz})/K_{\delta totcyco}$$
(Eq. 18)

$$\theta_{cyc1x}=\theta_{totcycx}-\theta_{px}-(M_{totcycx}-M_{px})/K_{\theta totcycxo}$$
(Eq. 19)

$$\theta_{cyc1y}=\theta_{totcycy}-\theta_{py}-(M_{totcycy}-M_{py})/K_{\theta totcycyo}$$
(Eq. 20)

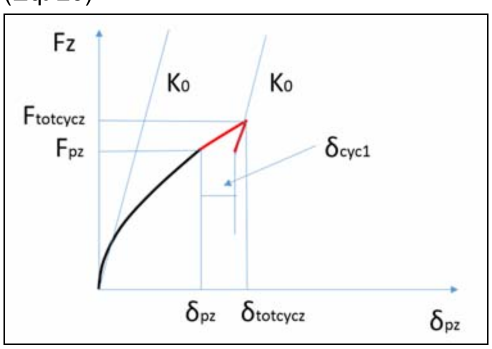

Figure 2. Settlement from first cycle of cyclic loading.

In (Eq. 18) to (Eq. 20) the paramenters $K_{\delta totcyco}$, $K_{\theta totcycxo}$ and $K_{\theta totcycyo}$ are the initial vertical stiffness calculated by SPLATE/FPLATES in the small load run:

$$K_{totcyco}=\frac{F_{totcyco}}{\delta_{totcyco}}$$
(Eq. 21)

$$K_{\theta totcycxo}=\frac{M_{totcycxo}}{\theta_{totcycxo}}$$
(Eq. 22)

$$K_{\theta totcycyo}=\frac{M_{totcycyo}}{\theta_{totcycyo}}$$
(Eq. 23)

Conservatively, it could be assumed that the unloading is infinitely rigid and that the first cycle displacements are equal to total cyclic minus permanent settlements:

$$\delta_{cyc1}=\delta_{totcycz}-\delta_{pz}$$
(Eq. 24)

3.6. Settlements and rotations due to creep

Creep settlements of foundations can be calculated based on the model presented by Athanasiu et. al. (2005):

$$\delta_c=\beta\cdot s_f\cdot A_\sigma\cdot\log_{10}(\frac{t}{t_o})$$
(Eq. 25)

δ_c is the creep settlement in linear phase (linear increase of settlement with logarithm of time), β is creep parameter for rock-fill material, A_σ is the area of effective vertical stress diagram under the foundation, and s_f is a bedrock slope factor, see Figure 3. For non-sloping bedrock surface under the foundation, s_f = 1, which is assumed in this paper. t is time elapsed from installation of foundation to the construction life time and t_0 is the reference time (adjusted so that the settlements in the diffusion phase are included). Creep parameter choice is based on Multiconsult experience with rock-fills (Athanasiu et. al., 2005), see

Table 1. The creep rotations are calculated as:

$$\theta_c=\theta_{st}\cdot(1+\frac{\delta_c}{\delta_{cr}})$$
(Eq. 26)

Table 1. Rock-fill creep settlement parameters (Athanasiu et. al., 2005).

Parameter	Explanation	Recommended value
t_0	Reference time	to=0.004 years *
β	Creep parameter	12E-06 m^2/kN **

**Adjusted so that the settlements in the diffusion phase is included*

***In Athanasiu et. al. (2005) a range of β is proposed (6E-6 to 25E-6 m^2/kN). A best estimate value of 12E-06 m^2/kN is used in this paper.*

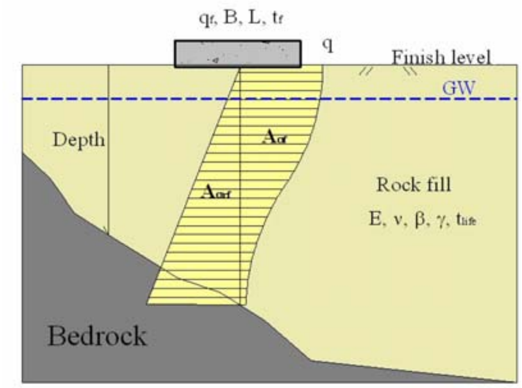

Figure 3. Vertical effective stress diagram under foundation

3.7. Resulting settlements and rotations

Total settlements are calculated as the sum of settlements from permanent loads, settlements from cyclic loading and creep settlements:

$$\delta_{tot} = \delta_{pz} + \delta_{acc} + \delta_c$$
$$= \delta_{pz} + (1+f_N)\delta_{cyc1} + \delta_c \quad \text{(Eq. 27)}$$

Similarly the rotations are calculated:

$$\theta_{tot} = \theta_{pz} + \theta_{acc} + \theta_c \quad \text{(Eq. 28)}$$

4. EXAMPLE ANALYSIS

In this example analysis, the differential settlements and rotations between two foundations (A and B) supporting the same crane rail will be assessed (see Figure 4 and Figure 5). It is assumed that foundation B is founded to bedrock while foundation A is founded on a 2.5-meter thick rock-fill layer above bedrock. The requirements to differential settlements between foundation A and foundation B is set by the structural discipline to 20 mm.

4.1. Geometry and loads

Figure 6 show the geometry of foundation A with dimensions 3.8 x 8.0 x 1.5 meters. Loads in the centre under the foundation are summarized in Table 2. The eccentricities relative to the centre of the foundation and the input eccentricities in SPLATE are calculated as described in sections 3.3 and 3.4. The cyclic loading consist of a crane load theoretically passing the foundation 35 times per day. The lifetime of the factory is 50 years. The total number of cycles during the lifetime is approximately N = 639 000.

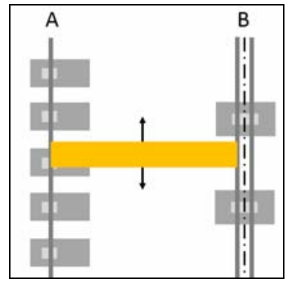

Figure 4. Extract of plan of foundations supporting main construction and crane rail

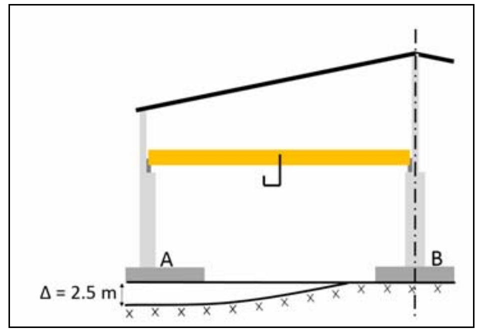

Figure 5. Simplified section of factory hall with foundations supporting main construction and crane rail.

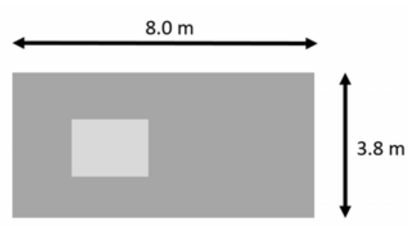

Figure 6. Geometry of foundation A

Table 2. Loads at center of bottom of foundation

Load	Fz (kN)	Mx (kNm)	My (kNm)
Permanent	-4880	-6670	1
Cyclic	-1740	2540	2.9
Total	-6620	-4130	3.9

4.2. Calculations

The first step is to check if foundation A is relatively stiff compared to the rock-fill, as described in section 3.1: $K_r \approx 0.51 < K_{rlim} = 5.51$. Since K_r is less than K_{rlim} the foundation plate is relatively stiff, and we can proceed using SPLATE for calculation of deformations. Settlements and rotations are calculated for permanent loads and total cyclic loads (cyclic + permanent) as described in section 3.3 and 3.4. The accumulated cyclic settlement is calculated from the first cycle settlement which is conservatively calculated assuming that the unloading is infinitely rigid, and that the first cycle displacements are equal to total cyclic settlements minus permanent settlements as described in section 3.5. Elastic deformation from weight of the foundation is calculated and subtracted, since this settlement contribution is assumed to be completed before the crane rail is installed, and thus can be adjusted for. Creep settlements and rotations are calculated for the permanent loads, using a creep parameter β=12E-06 m^2/kN and reference time t_0=0.004 as proposed in section 3.6. Creep settlements are calculated for a lifetime of 50 years.

4.3. Result

Deformation results from all steps are summarized in Table 3. As seen from the results, foundation A can experience a total settlement of about 2.8 cm:

$\delta_{tot} = \delta_{pz} + \delta_{acc} + \delta_c - \delta_{st}$ = 27.6 mm

Since foundation B is assumed founded to bedrock, the differential settlements is equal to the total settlement for foundation A. Thus, the differential settlements exceed the requirements set by the structural discipline (20 mm). As seen from Table 3, creep settlements contribute the most to the total deformation. The creep calculation is however very parameter sensitive, especially with regards to the creep parameter β. This is due to the parameter being based on empirical deformation data from large and high rock-fills and even rock-fill dam constructions. The creep settlement calculation is therefore considered conservative.

The differential settlements can be reduced by limiting the difference in depth to bedrock under the two foundation types. The foundations should be instrumented, enabling surveillance of deformations during operation of the plant. This way, measures can be taken when settlements and rotations are approaching the specified operational limits of the installations.

Table 3. Resulting settlements (in mm) and rotations (in radians)

Permanent	δ_{pz}= 8.0	θ_{ox}=1E-3	θ_{py}= 4E-7
Weigth of foundation	δ_{st}= 2.7	θ_{st}= 0	θ_{st} = 0
Perm+cycl	$\delta_{totcycz}$= 1.1	$\theta_{totcycx}$= 6E-4	$\theta_{totcycy}$=2E-3
First cycle	δ_{cyc1}= 2.9	θ_{cyc1x}= -4E-4	θ_{cyc1y}=1E-6
Acc. cyclic	δ_{acc}= 2.9	θ_{accx}= -4E-4	θ_{accy}=1E-6
Creep	δ_c= 19.4	θ_{cx}=3E-3	θ_{cy}=1E-6

CONCLUSIONS

This article has presented a method for estimating foundation rotations and settlements due to volumetric and shear strains in a rock-fill down to bedrock. The method considers a realistic representation of the rock-fill, and provides a conservative and efficient way of analysing a large number of foundations without the need for using advanced, time-consuming computer programs.

ACKNOWLEDGEMENTS

The authors would like to express their gratefulness towards Dr. Corneliu Athanasiu and Arne Schram Simonsen for valuable academic support.

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