Deformation Behavior of Clays Under Railway Traffic Loading

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ABSTRACT: In this paper, dynamic-cyclic loading in subgrade and subsoil resulting from railway traffic is briefly described by using some typical in-situ measurements. These data are then used as input parameters for investigating the deformation behavior of a medium plasticity clay under cyclic triaxial condition. The tests are done under the condition that the surface of soil samples is constructed as drainage boundary during cyclic loading. In the experimental investigation, static consolidation pressure as well as the maximum and frequency of cyclic loads are varied in some relevant zones. Based on the test results, some empiric relationships, especially permanent strain depending on the ratio of maximum cyclic stress to static stress, are proposed. Besides, the comparison between numerical and experimental results is also given.

1 INTRODUCTION

In Germany, there are at present two large railway projects in construction, that is, new high speed line Köln-Rhein/Main as well as Nürnberg-Ingolstadt (design train speed 300 km/h), where slab superstructures are applied. Under this condition, higher requirement of railway foundation construction should be met by applying DS 804 and DS 836 of the German Railway. According to this document, for example, allowable soil types as well as required density and stiffness of subgrade and subsoil are prescribed. In design, the proof of dynamic stability and long-term settlement resulting from railway traffic are necessary.

In some cases, however, railway tracks have to be constructed on the soils such as MH- and CH-Clays, which are normally not permissble for railway foundations of high speed line. Hier, the essential aspects are in regard to the dynamic instability and the large long-term deformation of the soils under dynamic-cyclic loading. As a result, some measurements in subsoils such as soil replacement or treatment may be necessary. The important question in this aspect is therefore, how extensive (deep and wide) such measurements should be for a safe and economical design.

In this paper, some empiric relationships describing the long-term deformation of a medium plasticity clay are deduced by using the cyclic triaxial test results simulating the cyclic loads from railway traffic. In addition, corresponding theoretical indication is also given.

2 DYNAMIC LOADING FROM RAILWAY TRAFFIC

The important physical variables describing the response of subgrade and subsoil to the railway traffic are mainly dynamic stress and its predominant frequency, vibrating velocity and acceleration as well as deformation, see Figure 1.

A detailed description and assessment regarding the dynamic loading in subgrade and subsoils under railway traffic is given in *Kempfert & Hu (1997)* and *(1999)*. In the following, only the results regarding dynamic stress and its predominant frequency, which are directly the input parameters for stress-controlled cyclic triaxial tests, are illustrated.
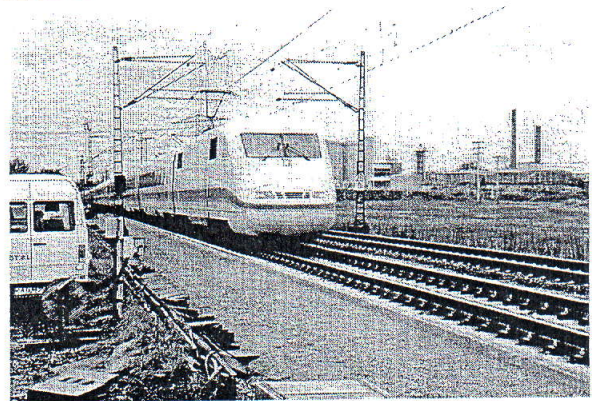

Figure 1. Measuring site by passing of a high speed train in Waghäusel, Germany.

The in-situ measurements under high speed lines showed that the maximum of dynamic stress in subgrade and subsoil is dependent on wheel set loads, train speed, installation depth of measuring instrument as well as superstructure form, see Figure 2 and 3.

It can be clearly seen that the dynamic stress σ_c in subgrade and subsoil is largely affected by train speed and superstructure. Up to about 150 km/h, there is no significant increase of dynamic compressive stress for ballasted track and slab system. After this point, it increases nearly linear with train speed up to about 300 km/h. Then, dynamic stress becomes almost constant again. This is generally the same tendency as theoretical prediction. In terms of our experience, stress amplification factor of 1.3 may be applied to the subsoil under slab superstructure and 1.6 to that under conventional ballasted track. The stiffer the superstructure, the smaller the measured dynamic pressure.

Upon the measurements, it has been found out that the attenuation of dynamic stress in depth under slab superstructure is slower than that under ballast superstructure. But the dependence of dynamic stress on depth can be well assessed using static finite element calculation under consideration of stress amplification factor.

For cyclic triaxial tests, another important input parameter „frequency of dynamic stress" is necessary. The evaluation of the measurements available indicated that for one soil element the form and frequency of resulting dynamic stress from railway traffic may vary and depends on superstructure, train type and speed. For a rough assessment of the predominant frequency of dynamic stress, the following relationship using the disturbance length L in Figure 4 may be applicable

$$f = v/L,$$

where v is train speed.
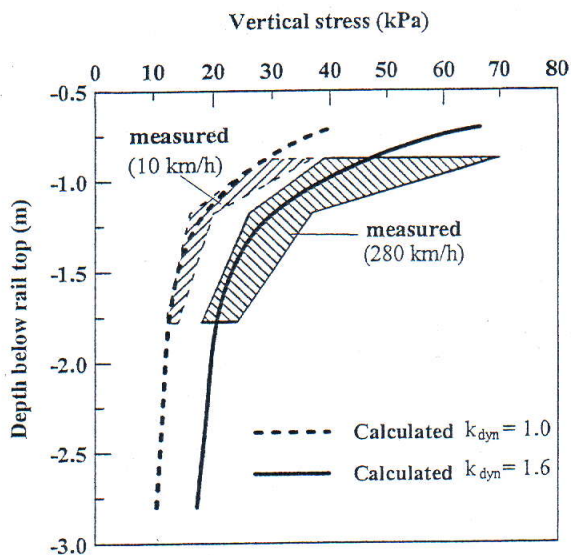
Figure 2. Dependency of the maximum of dynamic stress on train speed and depth, comparison of masured and numerical values, ballast superstructure, project Hannover-Würzburg.
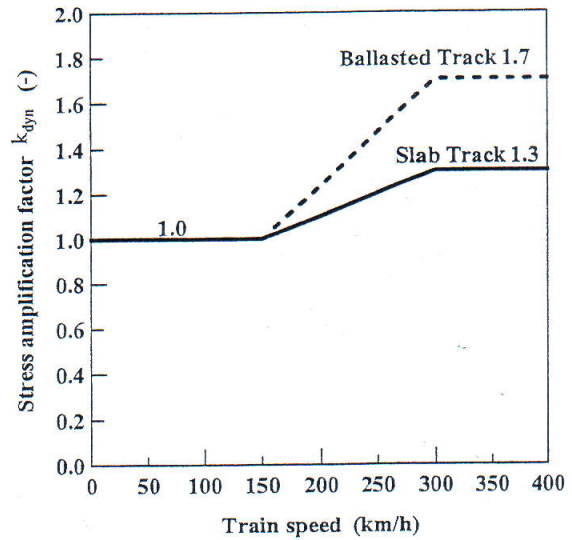

Figure 3. Idealized stress amplification factor k_{dyn} depending on train speed and superstructure based on in-situ measurements.

It should be pointed out that for the long-term deformation behavior of soils under railway traffic, static primary stress $\sigma_{3,0}$ plays also a very important role and should be therefore taken into consideration (normally < 75 kN/m^2).
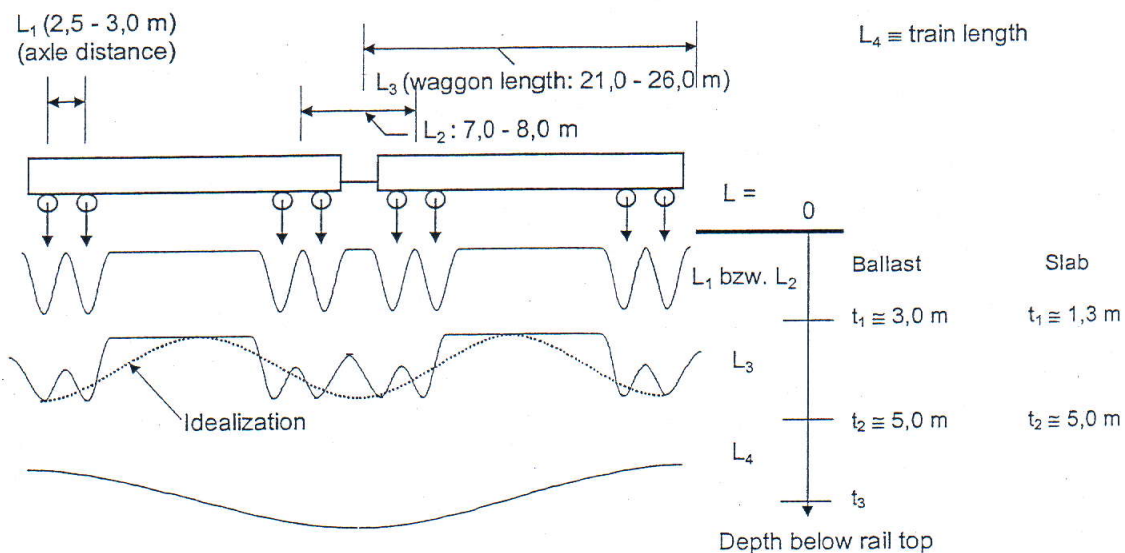

Figure 4. Disturbance length L depending on superstructure and depth, idealization after *Jaup (1999)*.

3 LABORATORY INVESTIGATION ON THE DEFORMATION BEHAVIOR OF A MEDIUM PLASTICITY CLAYS UNDER CYCLIC LOADS

3.1 Test apparatus and material

The test equipment used is illustrated in Figure 5. The static pressures are provided by a pneumatic system and the cyclic dynamic loading is applied through an electromagnetic dynamic system. It is possible to apply cyclic dynamic loading in both vertical and horizontal directions simultaneously. The maximum static cell pressure is up to 1500 kPa. And the maximum cyclic dynamic stress can be raised up to 100 kPa for $f = 1$ Hz (diameter of soil specimen $D = 10$ cm). The maximum frequency of dynamic stress is up to 10 Hz possible.
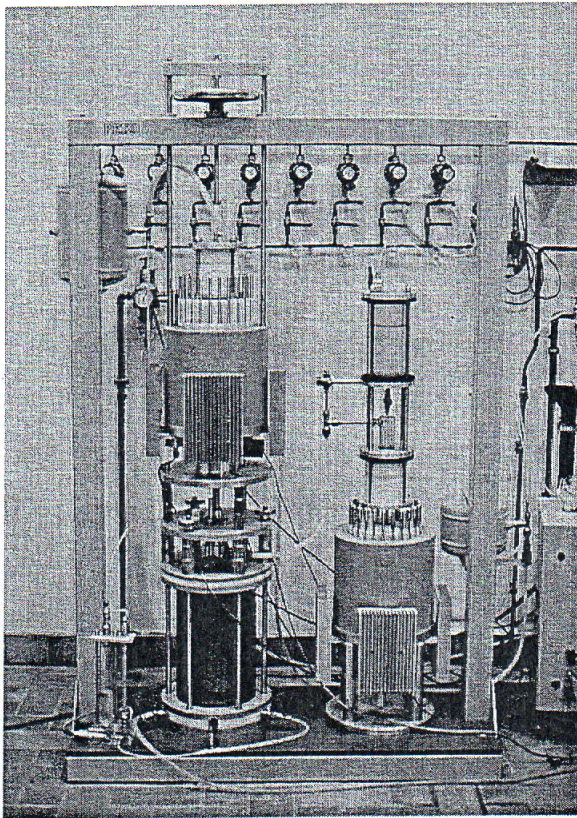

Figure 5. Cyclic triaxial test apparatus.

The test material is a clay of medium plasticity taken from an excavation site. The grain size distribution curve and the conventional soil-mechanical indexes are given in Figure 6.

The soil specimens were formed by using the Proctor compaction apparatus and have a size of 10 cm in diameter and 10 cm in height. They have a dry unit weight of 17.2 kN/m³ and a corresponding saturation grade of 95%.

To reduce the end restraint on the cap and base of soil specimens (H=D), the technique of greased end membranes was applied. The circumference surface of soil specimens were covered by porous strip paper to function as a drainage boundary. At the ends of the specimens, porous papers were used to seperate the soil specimens from lower and upper platens. In the middle of these platens a small hole filled with porous stone is directly connected to the drainage pipe.

The latex membrane was sealed at both ends onto the lower platen and upper platen by O-rubber rings.
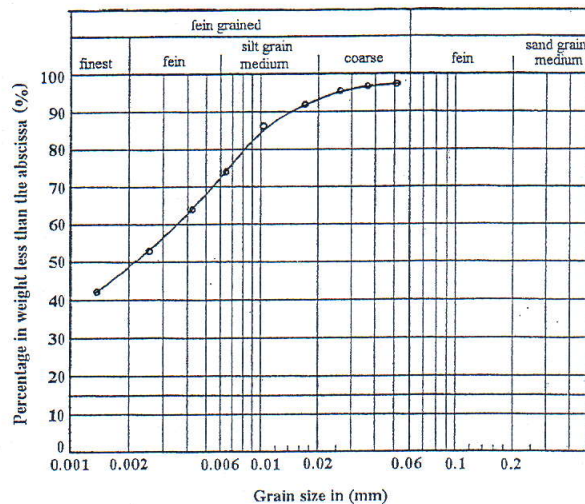
$w_L = 41.9\%$ $w_P = 18.4\%$ $w_n = 22.7\%$ $I_P = 23.5\%$
$I_C = 0.82$ $G_s = 2.75$ $w_{pr} = 16.4\%$ $\rho_{pr} = 18.1 \text{kN/m}^3$

Figure 6. The grain size distribution curve and the conventional soil mechanical indexes of the clay.

3.2 Input parameters and test program

Based on the results in section 2, following variations of three input parameters were taken into consideration in the experimental investigation:

$\sigma_{3,0} = 25/50/75 \text{ kN/m}^2$;
$\sigma_c = 20/40/60/80/100 \text{ kN/m}^2$;
$f = 0.25/1.0/2.5/5$ (sinusoidal function).

After the setting of the prepared soil specimens into the triaxial cell and the filling of the cell with demineralized water, saturation procedure began by applying the back pressure of 300 kPa. It took about 5 days to reach a saturation grade of 100%. Then, soil specimens were consolidated under assumed pressure. After the completion of consolidation the soil specimens were statically loaded up to the middle value of the assumed maximum dynamic stress in vertical direction and immediately cyclic dynamic stress was overlapped to the static one. From this time point, the cyclic dynamic loading begun.

During the cyclic tests the cell pressure and the back pressure were kept constant under the assumed values. Strictly, completely drained condition does not exist in this case, because the permeability of the tested soil is very low (about 10^{-8} cm/s) and the distribution of excess pore water pressure inside soil specimen may not be homogeneous. On the surface it should be zero, and increases up to the maximum in the middle of soil specimen. Therefore, partially drained condition is conceptually correct for this case. With the continuation of test the excess pore water pressure inside soil specimen will dissipate gradually and reach an equilibrating state.

Multi-stage technique was applied in the execution of the tests for different dynamic stress amplitudes, see Figure 7. For each loading step, the cyclic tests were continued until the permanent strain became unchanged.
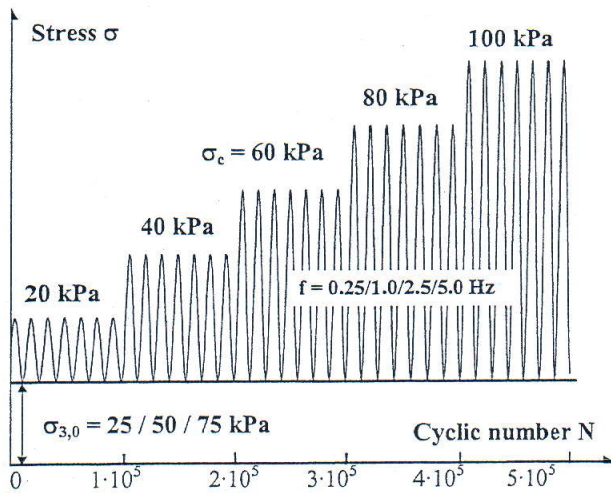
Figure 7. Test program: Multi-stage technique

3.3   Test results

Generally, the permanent strain reached stable state after about 100,000 cycles for each step. Exemplarily, the test results are illustrated in form of the ratio of permanet strain to that by $N = 10^5$ for the cases with $\sigma_{3,0} = 25$ kN/m², $\sigma_c = 60$ kN/m² (step 3) and f = 1 Hz/2.5 Hz as well as $\sigma_{3,0} = 50$ kN/m², $\sigma_c = 60$ kN/m² (step 3) and f = 0.25Hz / 2.5 Hz in Figure 8 and 9, respectively.
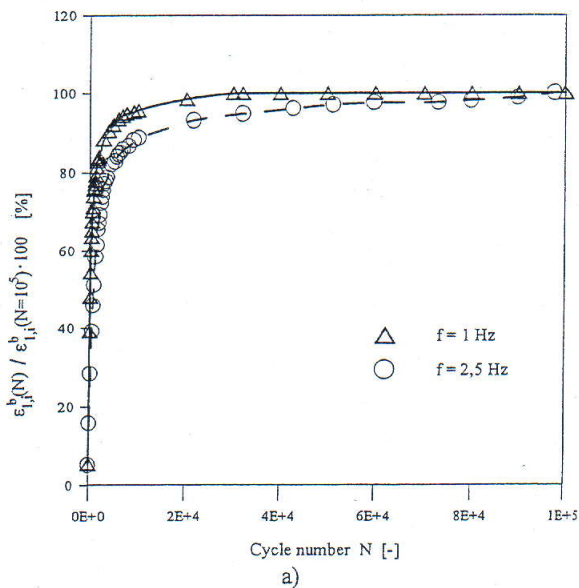
For the illustration using cycle number N, deviation between permanent strain for different frequencies is clear, while both curves become almost the same one, if the loading duration t is used as describing variable. This indicates that the loading duration t instead of cycle number N may be suitable for the description of the plastic deformation under cyclic condition.

In Figure 10, the permanent axial strain in stabile state is expressed as a function of $\sigma_c/\sigma_{3,0}$ for f = 0.25 Hz, 1 Hz and 2.5 Hz, respectively. It is evident that for one frequency all test points at different static and dynamic stresses nearly fall to the same curve.

The normalized test curves can be approximately expressed by using the following polynomial function:

$$\varepsilon_p^a = \alpha \cdot \left(\frac{\sigma_c}{\sigma_{3,0}}\right) + \beta \cdot \left(\frac{\sigma_c}{\sigma_{3,0}}\right)^2,$$

where:

α and β: coefficients of the regression curves.

The comparison of the curves by different fre-quencies showed that frequency has an influence on permanent strain in the way that under the same other conditions lower frequency may result in larger permanent strain. The further investigation is necessary for the development of an empiric relationship describing this behavior.
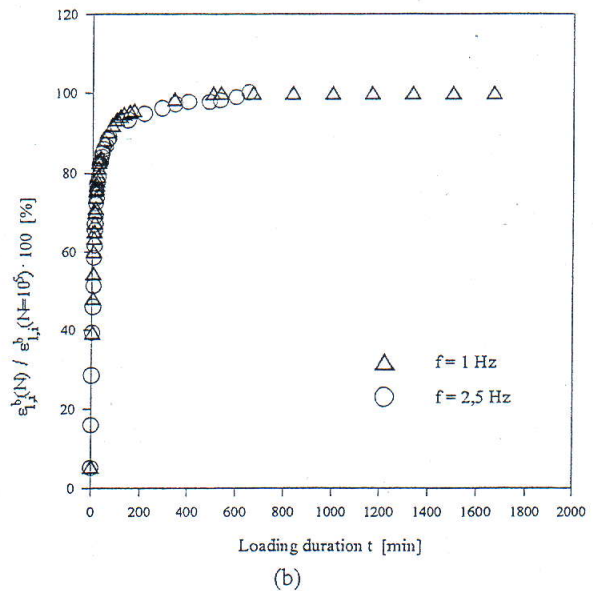

Figure 8. Permanent axial strain as a function of cycle number N (a) and loading duration t (b), $\sigma_{3,0} = 25$ kN/m², $\sigma_c = 60$ kN/m² (step 3) and f = 1/2.5 Hz.
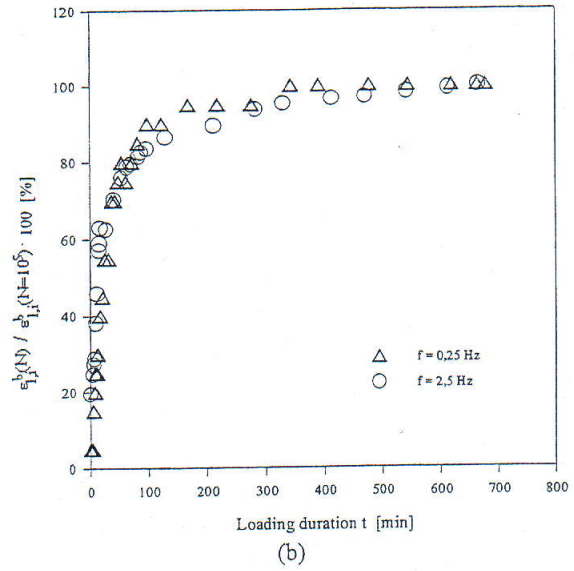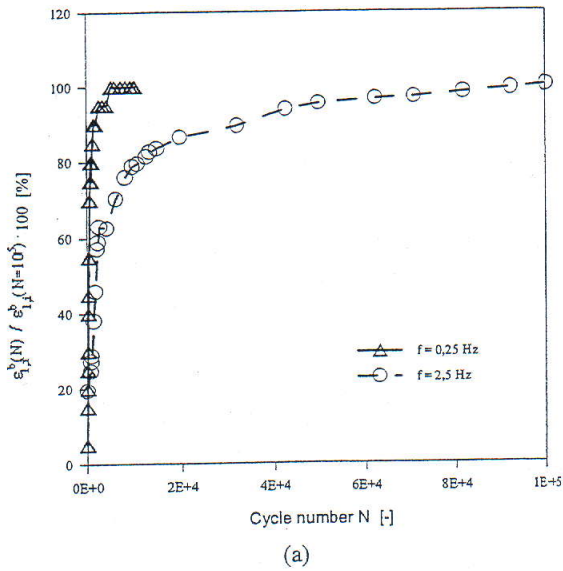
Figure 9. Permanent axial strain as a function of cycle number N (a) and loading duration t (b), $\sigma_{3,0} = 50$ kN/m², $\sigma_c = 60$ kN/m² (step 3) and f = 0.25/2.5 Hz.

a) f = 0.25 Hz
$\triangle$ $\sigma_{3,0} = 50$ kN/m²
$\diamond$ $\sigma_{3,0} = 75$ kN/m²

b) f = 1 Hz
$\bigcirc$ $\sigma_{3,0} = 25$ kN/m²
$\triangle$ $\sigma_{3,0} = 50$ kN/m²
$\diamond$ $\sigma_{3,0} = 75$ kN/m²
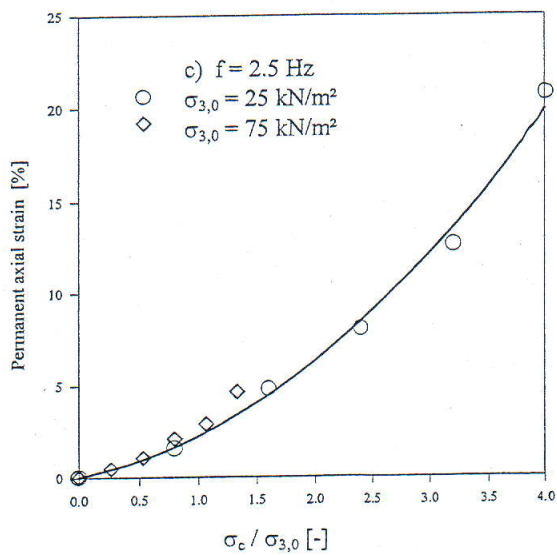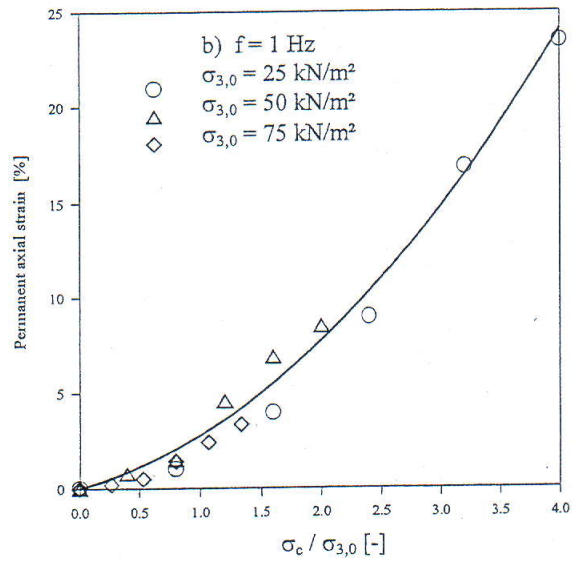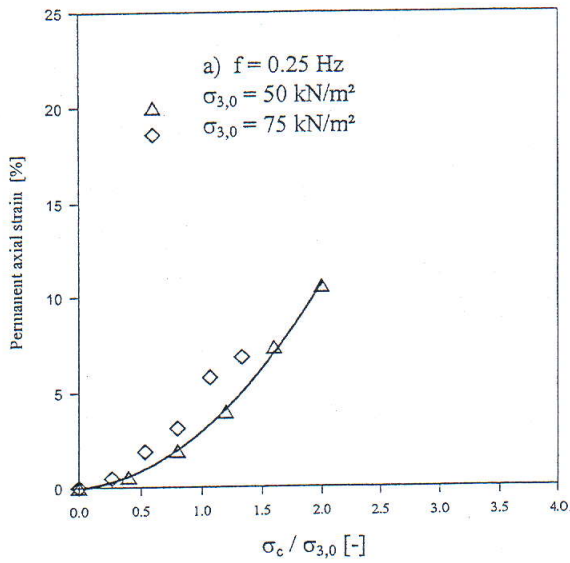
Figure 10. Permanent axial strain as a function of $\sigma_c/\sigma_{3,0}$.

4 THEORETICAL INDICATION

In *Hu (2000)*, a semi-theoretical model (GeoCycl) has been developed for a quantative description of stress - strain - cycle number - relationship of normally saturated clays under cyclic loading conditions, in which excess pore water pressure is seen as a controlling parameter for determining the first undrained plastic deformation and the subsequently resulting drained plastic deformation. The back-calculation of a test is given in Figure 11.

In the first two steps, good agreement is achieved. Large deviation begins from the third step, which indicates a stiffer behavior from the experiment than the theoretical predictions. This may be put down to the strengthening effect resulted from the multi-stage technique being not included in the theoretical model.
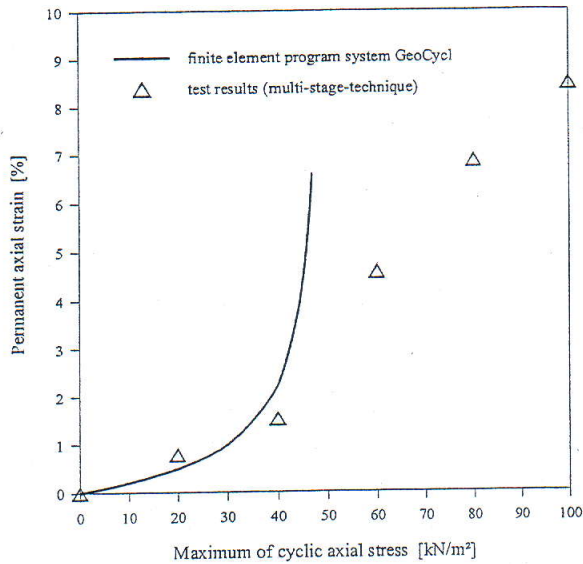

c) f = 2.5 Hz
$\bigcirc$ $\sigma_{3,0} = 25$ kN/m²
$\diamond$ $\sigma_{3,0} = 75$ kN/m²

Figure 11. Comparison of numerical and experimental results for the case $\sigma_{3,0} = 50$ kN/m², f = 1Hz.

5 CONCLUSIONS

Based on the availabile in-situ measurements in subgrade and subsoil by train passings, the influence of superstructure, train speed and depth is illustrated. These results have been used as input parameters for the experimental investigation on the long-term deformation behavior of clays under railway traffic.

The cyclic triaxial tests on a medium plastic clay showed the influence of the ratio $\sigma_c/\sigma_{3,0}$ and frequency f on the plastic axial strain. An empiric relationship has been proposed for the relationship between ε and $\sigma_c/\sigma_{3,0}$. Further experimental data are necessary for a quantative description of the influence of frequency on plastic deformation.

ACKNOWLEDGEMENTS

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