Static and dynamic plate loading tests of stabilized soil samples used for riverbank consolidation

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Abstract. Building of an experimental slope protection system on Căpuș river, near Cluj presented the opportunity of in situ testing of stabilized soils. Different hydraulic binder was used on each side of the river, so this testing series provided valuable data about deformability properties of the encountered soil types. There are some deformability parameters used in Romania which were “imported” at the specific request of foreign investors. The strain modulus, $E_v$, is a parameter expressing the deformation characteristics of a soil and is calculated taking values from the load-settlement curve obtained from the first and second loading cycle, on a static plate load test. In earthworks, the dynamic plate load test using the Light Falling Weight Deflectometer may be used for testing load-bearing capacity as an alternative to the static plate load test which provides the strain modulus, $E_v$, parameter. Dynamic modulus of deformation $E_{vd}$ is a parameter for the deformability of soil under a defined, vertical impact load with the impact duration. Its value is being calculated with the maximum settlement of the load plate. None of these methods made way into official Romanian standardisation, the $E_{vd}$ is subject of a technical agreement, which also contains the correlation of it with $E_v$. Conducting both static and dynamic loading tests enabled the verification of validity of relation between strain modulus and dynamic modulus.

1. Introduction

1.1. Objective of the study

This study is part of an experimental project which was carried out on “Căpuș” river from Cluj county, by building a slope protection system on both sides of the riverbank. Riverbank stabilization was made from stabilized soils, using hydraulic binders from our partners the Lafarge Holcim Group Romania. The left bank was stabilized mixing the local soil with Doroport TB25© [1], thus building a small dam, as seen in figure 1. On the right side considering the steeper slope, a protection retaining wall was more suitable from a technologic point of view. This system was built using soil-Dorosol C30© [2] admixture. Construction of the dam and slope protection was made regarding values obtained from laboratory analysis. Hydraulic binder was spread across the width and length of the structures, then a heavy mixer added optimal moisture content and created the desired admixture on both sides of the river. Compaction works were made according to Romanian regulations [3], with successive layers of equal thickness. Figure 2 presents one step of the spreading and mixing of hydraulic binder. The construction process was described in detail in other publications of this research group [4].
Stabilized soils are commonly used in road works, but as the need for riverbank consolidation is arising, this method could be a cheap and environmentally friendly solution, because it uses local soils rather than concrete or crushed stone structures, therefore having a much lower carbon footprint. Some of the river dams from Transylvania were developed for cycling tracks (in Satu Mare for example). There are also maintenance works concerning the river bed, on which construction machinery can climb on the protection system. Consequently both systems were subjected to on site tests typically used on road beds.

1.2. Review of standards and procedures

1.2.1. State of the art. There are several studies concerning the conversion of static and dynamic load bearing capacity moduli. Tompai [5] proposed a correlation formula, and required target values. In another paper Abdulkareem [6] used Artificial Neural Network model to calculate dynamic deformation modulus, Evd and comparing with the regression statistical model. The results indicate that ANN model have the capability of predicting dynamic deformation modulus, Evd with a high degree of accuracy. Good correlations were obtained, which demonstrated that the LFWD (Light Falling Weight Deflectometer) can be reliably used to predict the modules obtained from plate load test and degree of compaction values, and hence can be used to evaluate the stiffness/strength parameters of shallow subgrade layers.

1.2.2. Static plate loading test (SPLT). This test consist in applying load in increments to a soil sample using a circular loading plate as seen in figure 3 and a loading device, then releasing the load in decrements, and the entire process being repeated. The average normal stress below the plate, $\sigma_0$, is plotted against the settlement, $s$, for each load increment so as to obtain a load-settlement curve.

According to DIN 18134 [7] to determine the strain modulus, $E_v$, the load shall be applied in not less than six stages, in approximately equal increments, until the required maximum normal stress is reached. Each increase in load (from stage to stage) shall be completed within one minute. The load shall be released in stages, to 50% and 25% of the maximum load and then to the load corresponding to the zero reading. Following that, a further (2nd) loading cycle shall be carried out, in which the load is to be increased only to the penultimate stage of the first cycle.

The strain modulus, $E_v$, is a parameter expressing the deformation characteristics of a soil, and is calculated taking values from the load-settlement curve obtained from the first and second loading cycle, from the gradient of the secant between points $0.3 \cdot \sigma_{0\text{max}}$ and $0.7 \cdot \sigma_{0\text{max}}$.

Calculation of the strain moduli of the first and the second loading cycle shall be based on smooth load - settlement curves. These shall be expressed by calculating the settlement, $s$, at the centre of the loading plate using the equation:

$$ s = a_0 + a_1 \cdot \sigma_0 + a_2 \cdot \sigma_0^2 $$  \hspace{1cm} (1)

where:

$\sigma_0$ - is the average normal stress below the plate, in MN/m$^2$;
a₀, a₁, a₂ - are factors, in mm/MN²/m⁴, which consider different sums of total and partial settlement, respectively sums and sum of products of applied pressure, and the multiplication of pressure by settlement;

For determining the factors, a value of s equal to zero shall be ignored.

The strain modulus, \( E_v \), in MN/m², shall be calculated using the following equation:

\[
E_v = 1.5 \times r \times \frac{1}{a_1 + a_2 + \sigma_{0 \text{ max}}} \tag{2}
\]

where:

- \( r \) - is the radius of the loading plate, in mm;
- \( \sigma_{0 \text{ max}} \) - is the maximum average normal stress, in MN/m²;

As the testing procedures describe three stages, a loading stage, an unloading stage and a reloading stage we can describe two values for the strain modulus value, distinct for every loading stage: \( E_{v1} \) and \( E_{v2} \).

1.2.3. Dynamic plate loading test (DPLT). Dynamic test procedures have been developed in various countries to enable fast testing of constructed layers of earth under load conditions approximating those imposed by road traffic. The following described dynamic plate load test differs from the static plate load test (according to DIN 18134 [7]) in that the load is generated by a damped impact [8]. The impact activates forces of inertia in the soil and in the tester, and these have an effect on the movements which have been generated. In analogy to the static plate load test, also for the dynamic plate load test, a load plate with a 300 mm diameter is used, as seen in figure 4.

The dynamic plate-load test is suitable to determine the bearing capacity and the reached compaction quality of soils in underground/substructure in earthwork and road construction.

Dynamic modulus of deformation \( E_{vd} \) is a parameter for the deformability of soil under a defined, vertical impact load with the impact duration \( t_{\text{max}} \). Its value is being calculated with the maximum settlement \( s_{\text{max}} \) of the load plate as follows according to the formula:

\[
E_{vd} = 1.5 \times r \times \frac{\sigma_{\text{max}}}{s_{\text{max}}} \tag{3}
\]

where:

- \( s_{\text{max}} \) - average value of the settlements \( s_{\text{max}1}, s_{\text{max}2}, s_{\text{max}3} \) out of 3 measuring impacts (after 3 preloading impacts);
- \( r \) - is the radius of the loading plate, in mm;
- \( \sigma_{\text{max}} \) - normal stress under the load plate (0.1 MN/m²);

Figure 4. Dynamic plate loading test equipment.
1.2.4. Correlation between testing procedures. The situation of having two different types of testing procedures, based on different principles of load application, and one of them being significantly shorter and more convenient than the other led to the necessity of finding a relation between the strain modulus, \( E_v \), and the dynamic modulus of deformation \( E_{vd} \). A technical agreement [9] was put in practice, which contained the technical sheet of the equipment [10], defining the link between the two parameters in the following relationship:

\[
E_{v2} = 600 \times \ln \frac{300}{300 - E_{vd}}
\]

where:
- \( E_{v2} \) - strain modulus from the second loading cycle of the static plate loading test;
- \( E_{vd} \) - dynamic deformation modulus from the dynamic plate loading test.

2. Materials and methods

2.1. In situ conditions

Two different soil types were encountered on the sides of the riverbank. This fact led to using two different hydraulic binders, after performing a series of geotechnical analysis. Stabilization effects on shear strength parameters (cohesion, internal friction angle), and oedometric modulus were presented in previous papers [11]. Freeze-thaw resistance and testing also made the object of a separate study [12]. Doroprot TB25® was used on the left side, because the soil there was identified as sandy clay, and Dorosol C30® was mixed with the soil from the right side which had a higher content of sand, being described as a clayey sand. From an economic point of view 3% and 5% hydraulic binder content was considered.

![Figure 5. Testing point displacement on site.](image-url)
2.2. Static plate loading test (SPLT)
Performing the static plate loading test lead to the results presented in figure 6 and 7 for Point P1, located on the left side (blue points - first loading cycle, green points - unloading cycle, red points - second loading cycle):

![Figure 6. SPLT test results after 7 days curing time on the left embankment, point P1.](image1)

![Figure 7. SPLT test results after 28 days curing time on the left embankment, point P1.](image2)

The difference between strain modulus is notable on both first and second loading cycle. Testing on the right side provided slightly better results, as it seems sandy soil combined with Dorosol C30© is less deformable. Although initially the right embankment had slightly larger settlements, it seems that the stabilized sandy soil has greater reserves in terms of strain modulus $E_{v2}$, on the second loading cycle. Results and stress-settlement functions are presented in figures 8 and 9.

![Figure 8. SPLT test results after 7 days curing time on the right embankment, point P2.](image3)

![Figure 9. SPLT test results after 28 days curing time on the right embankment, point P2.](image4)
2.3. Dynamic plate loading test (DPLT)

The results of the DPLT tests performed on the left side are shown in figures 10, 11, 12:

Point D1 was probably set on a zone which wasn’t homogeneously mixed, this being the cause of the difference between the resulting dynamic modulus of deformation $E_{vd}$. Due to the execution technology which requires a chained mixer which follows a spreader device the presence of such points on top layers is inherent. The set of tests performed after 28 days from construction showed an unquestionable improvement of the dynamic modulus of deformation $E_{vd}$ on all three zones (considered after shifting points 1.00 m leftward). The results are presented in figures 13, 14, 15.
Testing procedures were identical for the right embankment, and the results are presented in figures 16, 17, 18:

A weaker zone is also present on the right side, on the zone around point D6. The values of the set of tests performed after 28 days show the same evolution as in the case of the left embankment. The results are presented in figures 18, 19, 20.

Figure 16. DPLT test results after 7 days curing time on the right embankment, point D4.

Figure 17. DPLT test results after 7 days curing time on the right embankment, point D5.

Figure 18. DPLT test results after 7 days curing time on the right embankment, point D6.

Figure 18. DPLT test results after 7 days curing time on the left embankment, point D4+1.00 m.

Figure 19. DPLT test results after 28 days curing time on the left embankment, point D5+1.00 m.

Figure 20. DPLT test results after 28 days curing time on the left embankment, point D6+1.00 m.
2.4. Correlation between strain modulus ($E_{v2}$) and dynamic modulus of deformation ($E_{vd}$)

The results obtained in situ permit a verification of relation (4) for the test performed at 7 and 28 days after stabilization.

2.4.1. Point P1 - left embankment, after 7 days

**Table 1.** Measured and deducted strain modulus ($E_{v2}$).

| $E_{vd}$ | $E_{v2}$ from relation | $E_{v2}$ measured on site |
|----------|------------------------|---------------------------|
| [MN/m$^2$] | [MN/m$^2$] | [MN/m$^2$] |
| D1 | 58.30 | 129.65 |
| D2 | 105.10 | 258.78 |
| D3 | 101.80 | 248.70 | 116.50 |
| Average | 88.40 | 209.45 |

2.4.2. Point P1 - left embankment, after 28 days

**Table 2.** Measured and deducted strain modulus ($E_{v2}$).

| $E_{vd}$ | $E_{v2}$ from relation | $E_{v2}$ measured on site |
|----------|------------------------|---------------------------|
| [MN/m$^2$] | [MN/m$^2$] | [MN/m$^2$] |
| D1+1.00 | 78.70 | 182.56 |
| D2+1.00 | 140.60 | 379.42 |
| D3+1.00 | 138.90 | 373.05 | 228.20 |
| Average | 119.40 | 304.50 |

2.4.3. Point P2 - right embankment, after 7 days

**Table 3.** Measured and deducted strain modulus ($E_{v2}$).

| $E_{vd}$ | $E_{v2}$ from relation | $E_{v2}$ measured on site |
|----------|------------------------|---------------------------|
| [MN/m$^2$] | [MN/m$^2$] | [MN/m$^2$] |
| D4 | 97.00 | 234.35 |
| D5 | 106.60 | 263.41 |
| D6 | 88.60 | 210.02 | 93.90 |
| Average | 97.40 | 235.53 |

2.4.4. Point P2 - right embankment, after 28 days

**Table 4.** Measured and deducted strain modulus ($E_{v2}$).

| $E_{vd}$ | $E_{v2}$ from relation | $E_{v2}$ measured on site |
|----------|------------------------|---------------------------|
| [MN/m$^2$] | [MN/m$^2$] | [MN/m$^2$] |
| D4+1.00 | 123.60 | 318.62 |
| D5+1.00 | 151.00 | 419.90 |
| D6+1.00 | 90.00 | 214.00 | 308.6 |
| Average | 121.53 | 311.62 |
3. Results and discussion

Results for deducted and measured strain modulus from point 2.4 are quite different. This seems to confirm the assumption from the German standard [4], which states at point 1, Field Application and Purpose: “The application of the dynamic plate load test is not permitted for the dynamic modulus of deformation $E_{vd}$ above 70 MN/m², because in this range the LDWT can not be calibrated sufficiently”. This statement, however, doesn’t appear in the user manual [8], nor in the technical agreement [7]. As we can see, having values consistently above 70 MN/m², by applying relation (4) one dangerously over-estimates the value of the strain modulus $E_{v2}$, from the second loading cycle. The relationship between the values of the two parameters is interesting even considering that testing points where the dynamic deformation modulus was below or slightly above the specified limit value of 70 MN/m². On point D1, from the left embankment, $E_{vd}$ is $58.30$ MN/m², resulting an $E_{v2}$ of $129.65$ MN/m². The measured $E_{v2}$ in the same zone is $116.50$ MN/m², 10% below the calculated value. Considering another point, D1+1.00 m $E_{vd}$ is $78.70$ MN/m², resulting an $E_{v2}$ of $182.56$ MN/m². The measured $E_{v2}$ in the same zone is $228.20$ MN/m², 25% above the calculated value. On the right embankment all results after 7 days curing time seem irrelevant, determined and measured values for strain modulus being far in between. Nonetheless the average value of the three points is very close to the measured $E_{v2}$ strain modulus. The comparison of the two test types aimed to study the validity of the correlation, when high values of dynamic deformation modulus are obtained, through soil stabilization with hydraulic binder. As the results from point 2.4 show, the relation (4) is mostly non-applicable.

4. Conclusions

Studying the results obtained with the SPLIT, two conclusions can be drawn. On one hand there is a considerable improvement between strain moduli ($E_{v2}$) obtained on both sides of the riverbank, between the tests conducted after 7 days from construction date, and 28 days respectively. On the left side which was stabilized with Doropor TB25© the strain modulus on the second loading cycle increased from $116.5$ MN/m² to $228.2$ MN/m², an addition of 49%. This tendency was even greater on the right side, where Dorosol C30© was used. $E_{v2}$ parameter went from $93.9$ MN/m² to $308.6$ MN/m², a growth of almost 70%. Therefore, both stabilized layers mobilize important deformability resistance reserves through their curing time.

This can also be seen in terms of settlement. On point P1, the average final settlement on the second loading cycle varied from 2.94 mm after 7 days to 1.91 mm after 28 days. Across the river, on point P2 this difference was 3.09 mm after 7 days, and 1.71 mm after 28 days. In both cases the settlement from the static plate loading test decreased about 30-40% on the given time interval.

Although proven as unreliable for determining the strain modulus values, the dynamic plate tests revealed high values for the $E_{vd}$ parameter, peaking the usual values obtained in road sub-bases. A clayey or sandy soil as found in its natural state on both embankments wouldn’t have a value above 40 MN/m², so hydraulic binder stabilization was a strong input in these structures. If this technology is chosen for riverbank consolidation, there is no problem in further using the structure for cycle tracks or maintenance works, as described in the introduction.

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