ENGINEERING TRANSACTIONS • *Engng. Trans.* • **64**, 4, 493–499, 2016
Polish Academy of Sciences • Institute of Fundamental Technological Research (IPPT PAN)
National Engineering School of Metz (ENIM) • Poznan University of Technology

Hysteretic Live Load Effect in Soil-Steel Structure

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This paper deals with the mechanical behaviour of soil-steel structures subjected to live loads. The results of the full scale experiment show that the deformation of such structures is affected not only by the location and intensity of the load, but also by the direction of its movement. The first part of the work reports the study of a railway viaduct located in Świdnica, Poland. In this study, the ST43-type locomotive is crossing the bridge one way and then back again. During such a loading cycle the deformation of the shell is registered. The graph of displacement in function of load position forms explicit hysteresis loop. Taking the advantage of the observation made in this experiment, a suitable 2D model of the structure is formulated and the test is simulated numerically. It is demonstrated that even quite a simple numerical model can give reliable results. Finally, it is proved that the hysteretic live load effect is associated with non-linear behaviour of the soil backfill as well as the shell-backfill contact zone.

Key words: flexible bridge, corrugated steel, viaduct, full scale testing, numerical simulation.

1. Introduction

Soil-steel structures are relatively inexpensive and reliable design technique for constructing engineering structures such as culverts, bridges or shallow tunnels. A soil-steel structure consists of a flexible shell that is backfilled with properly compacted soil. The mechanical behaviour of such structure results from the complexity of the interaction between soil backfill and flexible shell. As a consequence, the behaviour of entire object derives from both the characteristics of a steel shell and those of soil backfill. Thus, the behaviour of the structure can be non-linear. This is manifested, *inter alia*, by the hysteretic live load effect which has been identified experimentally by *in situ* tests, conducted on a few structures [1–3]. The measurements clearly show that the mechanical response of the structure subjected to live loads is affected not only by the location and intensity of the load, but also by the direction of its movement. The experimental evidence [e.g., 1–3] indicates that such a phenomenon is typical for the technology of soil-steel structures. In spite of that, the theoretical background of the live load effect provided in the literature is still very limited. The only attempt to modelling of this phenomenon was undertaken in [4] and in the former work of one of the authors in [5]. The modelling methodology provided in the present paper results in obtaining a much better agreement between the results of measurements and simulation. Eventually, it is demonstrated that the live load effect is associated not only with the frictional soil-steel contact but also with the non-linear behaviour of the soil itself.

2. In situ identification of the hysteretic live load effect

The hysteretic live load effect has been identified in the tests in which the truck or locomotive was crossing the bridge one way and then the other. The test has been conducted independently on a few engineering structures located on roads [1, 2] and railways [3].

In the analysis presented in the paper, the soil-steel viaduct structure along a railway line in Świdnica [3] is considered. The longitudinal cross-section of the shell is referred to as arc type SuperCor SC-19NA (Fig. 1). The shell is

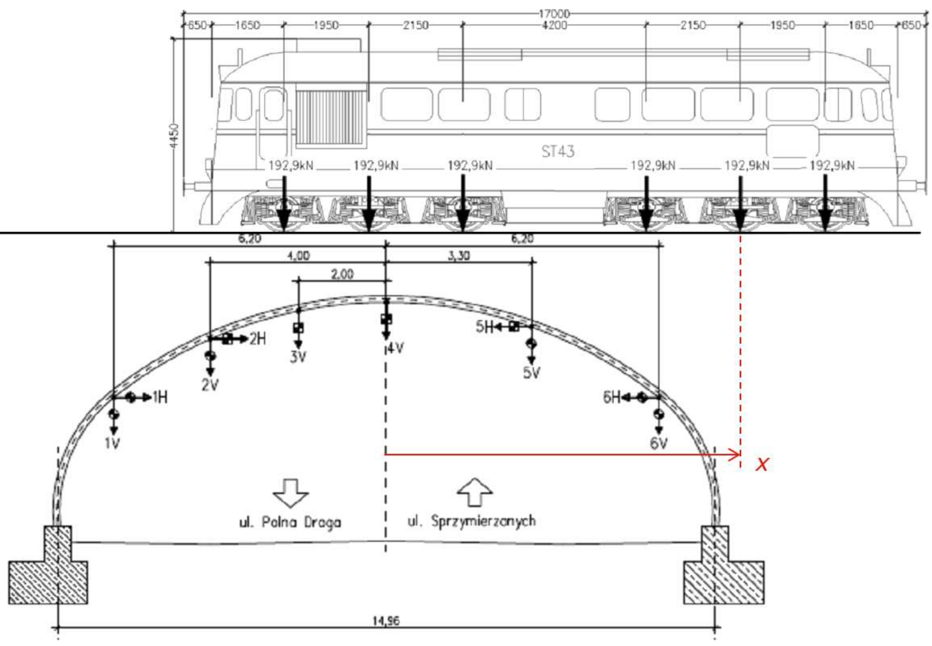

Fig. 1. The outline of the performed *in situ* live load test.

made of SC $380 \times 140 \times 7$ corrugated steel sheets reinforced with a cover of the same profile but made of thinner steel sheets, namely SC $380 \times 140 \times 5.5$. Span length of the structure is equal to $L = 15.0$ m. Height of the clearance is $h = 5.232$ m and curvature radius of the upper arc $R = 9.930$ m. A width of the shell changes with the height and equals $B_b = 26.3$ m at the bottom and $B_t = 13.0$ m at the top. The total structural height of the viaduct is $h_k = 1.60$ m. It includes the height of the shell cross-section, the minimal backfill thickness in the central axis of the object as well as the track structure. The live load test consists in the measurements of shell displacement induced by the moving load. The test was conducted with the use of ST43-type locomotive as a load. In the static test scheme, denoted as S2 in the original research [3], the reference points of measuring base are distributed along a circumferential line on the lower surface of the shell (Fig. 1). The position of the locomotive along the viaduct is determined by the variable x, standing for the distance between the middle axle of the front (right) bogie and the central axis of the viaduct (see Fig. 1). The displacements are measured using dial indicators with a reading accuracy of 0.01 mm.

The results of measurements – the graph of vertical displacement at reference point 4 versus the load position x during two subsequent passes in the opposite directions, are shown in Fig. 2.

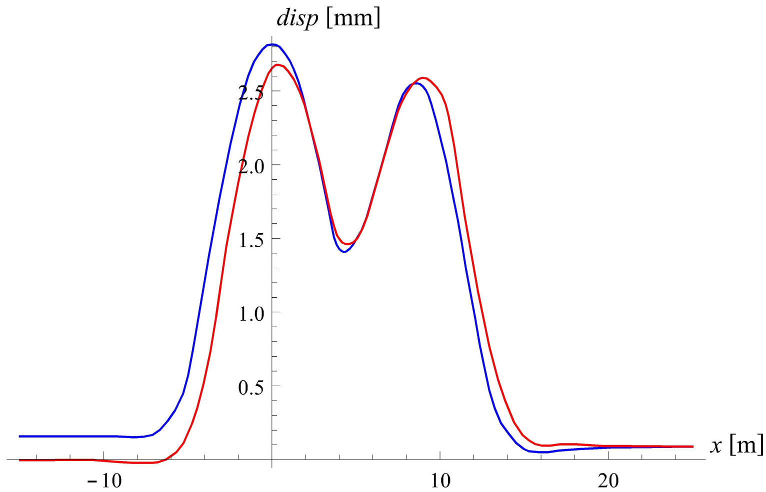

FIG. 2. Vertical displacement of the shell key point (displacement 4V): red line – the initial pass from the left to the right, blue line – return (result of the *in situ* test).

The plot forms explicit hysteresis loop – the parts of the plot, corresponding to particular directions of movement, are shifted in the direction of the locomotive passage. Furthermore, the local maxima are of the different values in the subsequent passages. Such effect is a characteristic feature of soil-steel structures in which a flexible shell interacts with the soil backfill. This is favourable in general as it enables utilizing a much lighter structure of arc in comparison to other bridge technologies. On the other hand, the presented observations indicate that some dissipative processes occur in the structure during the live load. Thus, understanding the causes of this phenomenon and the ability of predicting its consequences is very important in both design and operation of such objects. A valuable tool that helps understanding the mechanical behaviour of considered type of structure is numerical analysis, addressed in the next section.

3. Numerical modelling

The test, described in the preceding section, has been simulated using Itasca FLAC 7.0 software [6], based on the finite volume method. The software is dedicated to solving elastic-plastic deformation problems. The approach of FLAC software is based on a solution of dynamic equations of motion in terms of explicit finite difference scheme with the utilization of artificial, so-called nonviscous damping as a method for reaching static equilibrium. Consequently, the approach allows to deal with the plasticity problems involving construction phases or semi-static live loads.

The modelling procedure applied in the considered case is based on the procedure proposed in [5]. Unlike the former approach, a constitutive model of the soil medium is an elastic-perfectly plastic one in the present study. A Coulomb-Mohr plasticity function with a non-associated flow rule is assumed. The material parameters correspond to those of coarse sand in a dense state of compaction, i.e., Young's modulus $E = 150$ MPa, Poisson's ratio $\nu = 0.25$, density $\rho = 1.9$ t/m^3, cohesion $c = 15$ kPa, angle of internal friction $\varphi = 34°$ and dilatancy angle $\psi = 3.4°$. Non-zero value of cohesion, the so-called apparent cohesion, is adopted based on the Fredlund model [7]. The steel shell as well as the track structure is modelled with the use of beam linear elastic elements. Furthermore, the shell and the soil medium are connected through one-sided frictional interface. Shear stress in the contact zone is limited according to Coulomb's condition:

$$|\tau| \leqslant a - \sigma \tan \delta, \tag{3.1}$$

where $|\tau|$ – the absolute value of tangential stress at the interface, σ – normal stress, $\delta = \frac{2}{3}\varphi = 22.7°$, and $a = 0$ denotes the angle of friction in contact zone and adhesion, respectively. The dilatancy angle is $\psi = 0$; the geometry of the model is presented in Fig. 3.

The simulation includes the following stages of computation: first, only the deadweight of the shell and soil backfill is incorporated and the problem is solved. Next, the simplified structure of a track is placed. After that, the locomotive

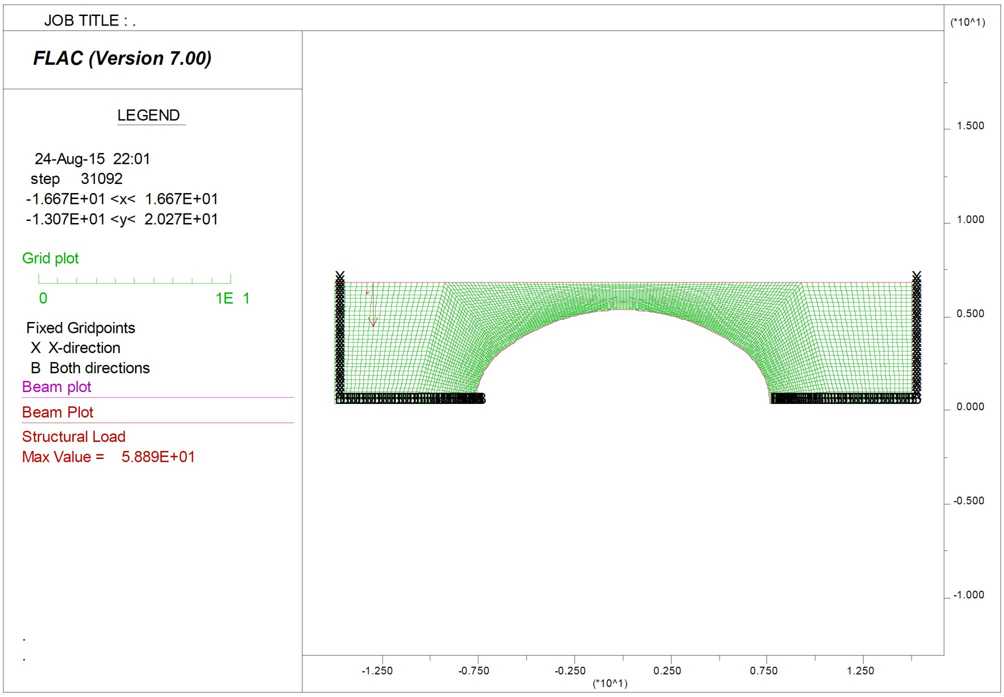

FIG. 3. Numerical model of the viaduct.

(load) is set in the initial position $x = -15.0$ m (see Fig. 3) and the problem is solved. Such sequence of computation brings the model to a reference state. This stage corresponds to the one at the beginning of the measurements in the experiment. Note that in the real test, one can measure only the relative increment of displacement, i.e., the difference between the actual displacement and the one at the reference state. Therefore, the adoption of a suitable reference state is necessary to enable the comparison of the real measurement and simulation results.

The next stage of computation procedure involves a semi-static moving load. This is accomplished as a sequence of static solutions for a number of consecutive locomotive locations. In other words, the following cycle is repeated: the load from the locomotive is moved by a specified short distance in the direction of the passage and the problem is solved, etc. The distance between subsequent positions of the load is chosen in such a manner that after 200 of such cycles the locomotive reaches position $x = 25.0$ m. After that, the direction of the load movement is changed so that the locomotive moves to the left. The analogous cycling is continued until the load position x reaches the initial position $x = -15.0$ m. The results of numerical simulation, corresponding to those in Fig. 2, are presented in Fig. 4.

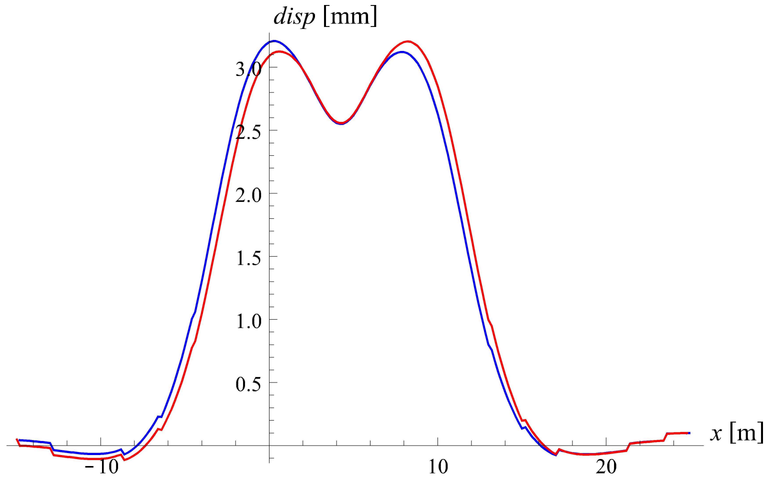

Fig. 4. Vertical displacement of the shell key point (displacement 4V): red line – the initial pass from the left to the right, blue line – return (result of the simulation).

The simulation results are in fair agreement with the experimental ones in both qualitative and quantitative aspects. The graph in Fig. 4, being a result of the simulation, forms a hysteresis loop. Similar to the experiment, the plot lines are shifted in the direction of the locomotive passage. Moreover, although the bogies transmit identical forces to the track, the maximum deflections induced by them are not equal. The greater displacement appears when the second bogie passes the reference point, i.e., left bogie in the passage to the right and right bogie in the passage to the left. The value of maximum displacement is slightly overestimated in the simulation. This could be a result of plain strain assumption. Furthermore, unlike the experiment, the shape of displacement graph is generally symmetric in simulation.

4. Summary and conclusions

The hysteretic effect has been identified by *in situ* live load test. It involves the measurements of shell displacements induced by the locomotive passing the viaduct one way and then the other. The results of the experiment clearly show that the deformation of the shell depends not only on the location of the load but also on the direction of the passage. The graph of the displacement forms hysteresis loop – the plot lines corresponding to subsequent runs, is shifted in the direction of the locomotive movement. Such an observation leads to a simple conclusion that some dissipative processes occur in the structure. Thus, the elastic-plastic constitutive model for soil backfill and one-sided frictional interface in the contact zone are adopted in the numerical model of the viaduct. The results of computations prove that these assumptions are sufficient enough to reconstruct the hysteresis effect in the simulation. Furthermore, the consistency of the measurements and the computations is fairly good, and it is better than in the former works [4, 5] that assumed a linear elastic model of soil backfill. Thus, it can be finally stated that the live load hysteretic effect in soil-steel structures results from the friction in the shell-backfill contact zone as well as from non-linear behaviour of the soil.

References

1. Machelski C., Antoniszyn G., *Influence of live loads on the soil-steel bridges*, Studia Geotechnica et Mechanica, **26**(3–4): 91–119, 2004.
2. Machelski C., Michalski B., *Deformations of soil-steel bridges*, Roads and Bridges, **4**(2): 91–110, 2005.
3. Machelski C., *Dependence of deformation of soil-shell structure on the direction of load passage*, Roads and Bridges, **13**(3): 223–233, 2014.
4. Machelski C., Marcinowski J., *Numerical modelling of moving load effect in a soil-steel bridge*, Archives of Institute of Civil Engineering, Poznan University of Technology **1**: 155–165. 2007.
5. Sobótka M., *Numerical simulation of hysteretic live load effect in a soil-steel bridge*, Studia Geotechnica et Mechanica, **36**(1): 104–110. 2014.
6. FLAC, *User's manual*, Itasca Consulting Group Inc., Minneapolis, 2007.
7. Fredlund D.G., Morgenstern N.R., Widger R.A., *The shear strength of unsaturated soils*, Canadian Geotechnical Journal, **15**(3): 313–321, 1978, doi: 10.1139/t78-029.

Received October 15, 2016; accepted version November 2, 2016.