The impact of backfill quality on soil-steel composite bridge response under seismic excitation

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Abstract. The soil-steel composite bridges, typically ranging from 3 to 25 m, can be used as an effective alternative for short-span bridges and culverts. They can meet the design and safety requirements as for traditional bridges, more rapidly and at lower costs. For these reasons, soil-steel bridges are increasingly being used in road and railway projects in many parts of the world. Due to the fact, the typical static and dynamic analyses of such bridges were already conducted many times, this paper focuses on the results of the numerical analysis of soil-steel composite bridge under seismic excitation. For these purposes a bridge with span of 17.67 m and height of 6.05 m was selected. Numerical analysis was conducted using the DIANA program based on finite element method. The density and Young modulus of the backfill were varied in the numerical models. A linear model with El Centro records and Time History analysis were used. The conclusions drawn from the study can be helpful for designers and researchers dealing with the soil-steel bridges, especially for the projects situated in the seismic areas.

1. Introduction

The soil-steel bridges can be met in various parts of the world. Their span usually does not exceed 25 meters, although it is possible to build objects of a span going up to even 40 meters. They are often a quite good alternative to traditional steel, concrete or timber bridges.

The soil-steel bridges have many advantages, amongst which the following may be included: (i) minimal use of steel, (ii) low construction and service costs, (iii) the possibility of prefabrication (partial or full prefabrication), (iv) the possibility of location the bridge in the weak ground, (v) fitting in the idea of the sustainable development. Despite numerous advantages, these structures also have some drawbacks such as: (i) a limited span, (ii) susceptibility to corrosion [1]. To some extent, it still remains unknown, how these bridges react when being impacted by seismic loads. So far, this problem has not been widely addressed in scientific works.

The main idea of the soil-steel bridges is designing a composite soil and steel structures in such a way that the loads applied to the structure do not exceed the load carrying capacity of composite bridge. Due to the phenomenon of arching in the soil and the flexibility of the steel shell, the carry of the large loads is possible. Usually, the soil-steel bridges carry the loads due to axial forces, with the minimum bending moments except of box culverts. One of the most important elements is a correct execution of the backfill surrounding the steel shell.
So far, the soil-steel bridges analyses have been carried out in the range of static loads [2,3] or dynamic loads [4,5]. Elshimi et al. [6] presented an experimental testing and numerical analysis of the culvert made from corrugated steel plates. The obtained results were also compared to the Canadian CHBDC code [7], and the maximum difference between experimental test and code results was 73%. On the other hands, Bayoglu Flener [8] analysed the influence of the backfill height on the values of internal forces. Two soil-steel structures with different spans and heights were used for the analysis. The significant differences were observed between the internal forces from the tests and the results obtained on the basis of the CHBDC code [7].

Structures subjected to seismic or paraseismic excitations are usually analysed using the Time History method, which is based on the step-by-step integration method [9,10]. For bridge structures that interact with the soil, the seismic analyses are most often conducted for reinforced concrete (RC) arch bridges or RC box culverts. Sawamura et al. [11] used the Time History method to analyse the impact of seismic excitations on the RC culverts. Maghgoub and El Naggar [12] analysed the impact of various seismic excitations on steel shell structures. The obtained values were compared to the CHBDC code [7]. It was found that compatibility of the numerical analysis with the code occurred only in the case of a short excitation, characterized by a high value of ground acceleration. In this case, the numerical analysis was performed using the FLAC program.

The main purpose of this paper is presenting the impact of the natural earthquake on the soil-steel bridge with the use of different soil parameters. Especially Young modulus and backfill density are varied. The selected bridge was subjected to numerical analysis using the DIANA FEA computer program and Time History method. The applied load is extreme El Centro benchmark excitation.

2. A short description of the soil-steel bridge

The analysed soil-steel bridge is located in Poland (Figure 1). This object is a passage for animals. The analysed object has the following parameters: the clear height of 6.05 m, the span of 17.67 m, the width of the shell in crown of 40.39 m, the width at the foundation of 53.83 m, the thickness of the steel shell of 0.007 m, the corrugation depth of 0.14 m, and the corrugation pitch of 0.38 m. The corrugated steel plate sheets were connected with one another using the bolts with a diameter of 20 mm. The bolts were tightened with a torque value of 350-400 Nm. The steel shell was fixed on RC foundations (made from concrete of C25/30) with the length of 53.83 m and the width of 4.0 m. The backfill surrounding the steel shell was made from aggregates of 10-32 mm and place with layers 0.2-0.3 m thick. In order to ensure proper interaction of the shell structure with the soil, the backfill was compacted to reach $I_D = 95\%$ according to the Normal Proctor scale. The maximum height of the backfill in the shell crown equals to 1.8 m.

Figure 1. The soil-steel bridge during construction.
3. Numerical analysis of soil-steel bridge

The DIANA FEA computer program [13] based on the finite element method (FEM) was used in the numerical analysis. The assumptions proposed by Maleska et al. [10] were used to build the numerical models:

- the corrugated steel plates were modelled as shell curved elements (Q24IF) with Young modulus of 205 GPa, Poisson ratio of 0.3, elastic-plastic model with density of 7850 kg/m³, the yield strength of steel of 235 MPa, area moment of inertia of the unit width of 21897.45 mm⁴/mm, cross section area of 8.867mm²/mm, and plate thickness of 0.007 m. The corrugated steel plate was modelled as a flat one with orthotropic characteristics. The transformation of the corrugation shell to the flat one was carried out according to the procedure contained in the works [10,14]. Based on the research carried out in [14], it was found out that the use of an orthotropic shell does not significantly affect the accuracy of the calculations.

- the backfill was modelled as solid elements (HX24L) with the Duncan-Chang nonlinear elastic hyperbolic model. The backfill parameters were: Poisson ratio of 0.2, dilation angle of 5°, angle of internal friction of 39°, cohesion of 3000 N, failure ratio \( R_f = 0.7 \), unloading-reloading stiffness \( E_{ur} = 1000 \) N/m², reference pressure \( P_{ref} = 101350 \) N/m², exponent for unloading reloading curve \( m = 0.25 \), exponent for backbone curve \( n = 1.1 \), minimum compressive stress 350 N/m², and minimum tangential stiffness of backbone curve \( E_{t,min} = 1200 \) N/m³. In order to determine the impact of the backfill quality on the behaviour of the bridge under seismic excitation, five soil models were used (Table 1). Young modulus and backfill density were varied, while the parameters of model 1 were the real data for the analysed bridge,

| Value               | Model 1 [10] | Model 2 [14] | Model 3 [15] | Model 4 [15] | Model 5 |
|---------------------|--------------|--------------|--------------|--------------|---------|
| Young modulus (MPa) | 100          | 200          | 114          | 240          | 150     |
| Density (kg/m³)     | 2050         | 2000         | 1600         | 2000         | 2000    |

- the connection between the backfill and the steel shell was modelled as automatic interface by applied function “Coulomb friction” with the angle of internal friction of 39°, dilation angle of 5°, rigidity of 100000 kN/m², and cohesion of 3000 N,

- the finite elements were modelled as quadratic elements with dimensions of 0.50×0.50 m for the backfill and the corrugated steel shell (Figure 2),

- the boundary conditions were modelled as non-transferable support of the shell walls and of all boundary walls of the backfill for x, y, z directions.

Figure 2. Numerical model of soil-steel bridge in the DIANA FEA program.
In the numerical analysis, the Time History method was applied, which allows determining the impact of seismic excitation on a soil-steel bridge. In the analysed cases, the El Centro seismic record form 1940 was used [16]. This earthquake record is considered as destructive and reaches 6.9 on the Richter scale. The ground acceleration for recording is equal to 3.44 m/s². The seismic tremor was applied in two directions, i.e. "X" (perpendicular to the bridge) and "Y" (parallel to the bridge). The obtained maximum values of displacements, internal forces and stresses are presented in Table 2.

**Table 2. Maximum values for steel shell and backfill caused by El Centro excitation.**

| Value                                      | Model 1   | Model 2   | Model 3   | Model 4   | Model 5   |
|--------------------------------------------|-----------|-----------|-----------|-----------|-----------|
| Direction of seismic loads application:    | X and Y   | X and Y   | X and Y   | X and Y   | X and Y   |
| Shell displacements (m)                    | 0.25      | 0.18      | 0.20      | 0.16      | 0.21      |
| Backfill displacements (m)                 | 0.25      | 0.18      | 0.20      | 0.16      | 0.21      |
| Stresses in steel shell (MPa)              | –108      | –77.2     | –84.1     | –69.9     | –89.2     |
| Stresses in backfill (MPa)                 | –1.778    | –2.241    | –1.476    | –2.551    | –1.941    |
| Axial thrusts in shell (kN/m)              | –10900    | –8113     | –8623     | –7405     | –9229     |
| Bending moments in shell (kNm/m)           | 66.16     | 35.05     | 45.44     | 30.00     | 45.51     |

The largest displacements of the steel shell (Figure 3) and backfill occurred for "Model 1", where the maximum value was 0.25 m. On the other hand, the smallest displacements were observed in "Model 4". In this case, they amounted to 0.16 m (Figure 4), which is 36% difference compared to the "Model 1". It is worth emphasizing that the displacements of the backfill and the steel shell were the same, which indicates the correct image of the interaction between the steel shell and the backfill. For the analysed soil models, the same displacements were obtained in both the "X" and "Y" directions. This indicates that the excitation direction is irrelevant as regards the shell and backfill displacements. The maximum displacements observed at the shell crown, in the middle part of the shell and they were directed downwards (deflection of the shell).

![Figure 3. Top view for the maximum displacements of the shell obtained from "Model 1".](image-url)
Figure 4. Distribution of backfill displacements obtained from "Model 4".

The highest stresses in the steel shell occurred in "Model 1" and their values were about \( -108 \) MPa (Figure 5). However, the smallest stresses were observed for "Model 4", where the values equalled nearly to \( -69.9 \) MPa. The difference from "Model 1" and "Model 4" was 35.3%. The maximum stresses in the particular models appeared in the vicinity of the shell supports, and they had a compressive nature. It should be noted that the location of maximum stresses is different in comparison to stresses obtained from the static or dynamic loads (usually it was at the shell crown or quarter points – depending on the shell shape).

Figure 5. A view of the maximum stresses in the shell obtained from "Model 1".

Maximum stresses in the backfill were observed for "Model 4" and amounted to \( -2.551 \) MPa (Figure 6). While the smallest stresses in the backfill occurred in "Model 3" and they were smaller by 42.1% than those of "Model 4", and their values amounted to \( -1.476 \) MPa (Figure 7). The maximum stresses in the backfill occurred near the shell supports and arrived the quarter points. It was noted that the directions of seismic excitation do not affect the obtained values of stresses in the backfill.

Figure 6. Distribution of stresses in the backfill obtained from "Model 4".
The maximum axial forces also occurred in "Model 1" and amounted to $-10900 \text{ kN/m}$ (Figure 8). The largest forces were the same in the "X" and "Y" direction of the seismic excitation. However, the smallest axial forces were observed for "Model 4". The axial forces were lower by about 32% compared to "Model 1" and amounted to $-7405 \text{ kN/m}$ (Figure 9). It is worth noting that the maximum axial forces were strongly compressive and occurred in the shell in the vicinity of the foundations. It was also observed that the obtained axial forces in the shell from the seismic excitation are much greater than those caused by the dynamic loads, e.g. train [5].

The highest values of bending moments were obtained for "Model 1". The maximum value was 66.16 kNm/m (Figure 10). Nevertheless, the smallest bending moment was 30.00 kNm/m and it was observed in "Model 4" (Figure 11). This is a value lower by 54.7% in comparison to the maximum bending moment obtained in "Model 1". The largest values occurred near the supports of the steel shell. They were observed in the same places as for axial forces and stresses, however, they were positive. It should be added that in the case of static or dynamic load, the maximum bending moments were usually located in the shell crown. It is also worth noting that the direction of load application is not important for the obtained values of bending moments. It should be also emphasized that the
amount of bending moments obtained from the seismic excitation is much greater than in the case of static or dynamic load [5,17].

![Figure 10](image1.png)

Figure 10. The distribution of the maximum bending moments in the shell in "Model 1".

![Figure 11](image2.png)

Figure 11. The distribution of the maximum bending moments in the shell in "Model 4".

4. Conclusion

As a result of the Time History analysis of the soil-steel bridge under the El Centro seismic excitation, the following conclusions can be drawn:

- the obtained results indicate that Young modulus is the most important factor. This is best seen on the basis of the results analysis from the "Model 1" and "Model 2". The difference in backfill density is very small (2.4%), while Young modulus values differ by as much as 50%. The results obtained from the "Model 2" were smaller than those of "Model 1" for: (i) displacements by 28%, (ii) stresses by 28.5%, (iii) axial forces by 25.6%, (iv) bending moments by 47%,
- the backfill density is also important for the obtained internal forces, displacements and stresses. It can be seen by comparing the results obtained from "Model 1" and "Model 3", where Young modules were similar to each other. In these models, the difference in Young modulus was about 14% between particular soil models. However, the difference in the backfill density was equal to 28%. It is worth noting that the differences in results for the steel shell between "Model 1" and "Model 3" were: (i) 20% for displacements, (ii) 22.1% for stresses, (iii) 20.1% for axial forces, (iv) 31.3% for bending moments,
- the direction of application of the seismic tremor ("X" - perpendicular and "Y" - parallel) does not affect the obtained results. In each of the considered soil models, the same results of numerical calculations were obtained (regardless of the tremor directions),
- the bending moments and axial forces in the steel shell caused by seismic excitation are much greater than those obtained during typical tests under static or dynamic loads, e.g. during the train or vehicle rides. It was also noticed that the location of bending moments and axial forces is different (near the shell support) than in the case acting on the dynamic load (the shell crown or quarter points),
- it was also observed that the place of occurrence of maximum axial forces, bending moments and stresses in the shell is the same in all the analysed numerical models. Maximum values of internal
forces and stresses occurred near the foundations of the soil-steel bridge and reached up to 1/3 of the height of the shell. In the case of displacements, the maximum values were observed near the crown of steel shell.

- the yield strength for steel has not been exceeded in any of the considered cases. The maximum stresses in the steel shell were equal to ~108 MPa, while the yield strength for the analysed bridge was 235 MPa.

In order to gain the more detailed knowledge of the behaviour of the soil-steel bridges subjected to natural earthquakes, further research related to this subject is necessary.

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