The technical issues described in the paper concern aspects of foundations of buried flexible steel structures.

The foundations of these structures are most frequently made as traditional “rigid” structures (which is related to their massiveness - most commonly reinforced concrete), or in the form of properly profiled soil foundations (depending on the shape of the coating). Comparison of the two issues of “vulnerability”, i.e. the bearing structure and the "rigidity" of foundations, is the main motivation to carry out testing and conduct an analysis in this area. The problems are discussed in the paper in the context of new developments in the field of “flexible” foundations of the structures in question. Further development analyses are currently in progress, which will be practically implemented in the form of appropriate guidelines. In the authors’ opinion, this will help to optimize the design of the in which the foundation of these structures.

Keywords: buried flexible steel structures, foundation, developmental trends, flexible foundations, laboratory tests, optimization.

1. INTRODUCTION

Considering the rapid expansion of transport infrastructure in Poland, modern solutions such as flexible structures are becoming increasingly popular in civil engineering. This is due to the indisputable advantages of the structures erected in this manner. This method can be also applied to buried shell structures made of corrugated sheet metal, such as culverts, wildlife crossings, and small bridges, and is used in increasingly greater number of massive bridging structures, including environmentally-friendly bridges.

The development of these technologies, however, is often ahead of the legislation and engineering practice.
The technical issues described in this paper refer to the aspects of making foundations for the “light” buried shell structures. The innovation of these structures has surpassed the methods of making foundations, which are most often rigid structures (and, due to their weight, are frequently made of reinforced concrete) [1] [2].

The comparison of these two issues—the flexibility of a supporting structure and the rigidity of its foundation—was the basis and incentive for carrying out the relevant research and analyses. Thus the above issues were thoroughly investigated, which was followed by live-scale laboratory tests, whose results are presented in this paper. Further development work is being carried out for possible implementation and for practical applications.

2. CURRENT FOUNDATION ENGINEERING OF FLEXIBLE STRUCTURES

It is commonly known that buried shell structures made of corrugated steel sheet are an important part of transport infrastructure, and are widely used in the construction of roads and railways. Their popularity in the Polish transport infrastructure is very high, and continues to grow along with the increase of the number of roads and railways.

The indisputable advantages of civil engineering structures made of corrugated sheet metal are as follows:

− versatility of application,
− high strength,
− high corrosion resistance,
− low maintenance costs.

It should be stressed that some solutions currently applied in these structures require broadly defined optimization. Therefore, it is necessary to further improve these structures, mostly to reduce project implementation times. The optimization refers not only to the development of innovative solutions, and the use of state-of-the-art construction materials, but also involves economic and environmental aspects.

As required by the applicable Polish laws, foundations need to be designed in compliance with a standard for reinforced concrete bridges. In this case, a foundation should be made as a massive continuous reinforced concrete structure, i.e., a strip footing.

The law, however, does not address the peculiarities of buried shell structures, which requires such foundations to be redesigned in terms of load-bearing capacity and, consequently, dimensions. This directly increases the duration and costs of projects.
For this reason, among others, such structures in recent years have been more and more frequently constructed with the use of flexible foundations, mostly in the form of corrugated steel sheet of various dimensions, thickness and corrugation density.

Such solutions were applied in a number of transport infrastructure facilities [12], [13] and so far there have been no objections related to their operation (i.e. load-bearing capacity, subsidence, etc.).

Examples of such structures are shown in Figures 1 to 3.

This method of making foundations for flexible shell structures appears to be more advantageous due to the uniformity of the overall structure. In this case both the structure and its foundation are flexible. Foundation depth should also be taken into consideration. In case of flexible foundations with appropriate characteristics of subsoil it is possible to ignore frost line, which otherwise is a key factor in case of rigid foundations. The conducted FEM analyses [20] indicate a high load-bearing capacity tolerance of flexible foundations made of corrugated sheet for variable characteristics of subsoil. Therefore, this paper aims to present, among other things, the options of widespread application flexible foundations in terms of future development trends.
Fig. 2. A detailed view of a flexible foundation made of corrugated sheet fixed to a high-corrugation steel shell structure

Fig. 3. Installation of a buried shell structure on a corrugated sheet foundation
3. RESULTS OF THE COMPARATIVE STUDY OF RIGID AND FLEXIBLE FOUNDATIONS

One of the authors of the paper was in charge of a number of studies carried out in the Road and Bridge Research Institute in Żmigród relating to live-scale shell structures, in terms of static loads, dynamic loads, and a combination of both, as well as in terms of fatigue and durability. The foundation conditions of these structures were also analyzed in these studies. The analyses of the behavior of these structures on the basis of these studies, among others, clearly show that the use of flexible foundations is technically feasible in this case.

The foundations can be made of e.g. corrugated sheet metal placed on soil and supporting the shell along its bottom edge.

The studies analyzed, among others, structures with two kinds of foundations, i.e. rigid (reinforced concrete foundations) and flexible (corrugated sheets arranged horizontally). The structures comprised two arch-shaped culverts made of helically corrugated steel pipe (HelCor) with identical dimensions. Each analyzed structure had a length of 4.00 m, a clear width of 2.50 m, and a clear height of 1.25 m.

It should be noted that the development of research models was accompanied by comprehensive studies of the soil – both subsoil and backfill. The analysis of compaction was carried out on a regular basis both during the foundation of the structure, as well as when respective layers of backfill were added [18].

The surcharge above the structures amounted to 0.60 m, which is the minimum for this type of structure for withstanding moving loads in compliance with top load class. The adopted minimum surcharge helped to carry out the comparative analysis of the behavior of the two structures in best conditions.

Figure 4 presents the metering diagram for both analyzed models.

![Diagram](image-url)

**Fig. 4.** Structure metering diagram for the study of models on a corrugated sheet metal foundation and a reinforced concrete foundation.
As the primary objective of this study was to demonstrate the differences in the behavior of buried shell structures on two types of foundation, the sensors and pressure meters used to analyze soil stress were located so as to obtain maximum possible reliable information on the actual behavior of the structure in the foundation area.

Table 1 presents a summary of the stress values under both foundations during backfilling the test models.

The diagram in Figure 5 presents the values of vertical displacement of the structure key after backfilling.

Table 1. Recorded values of stress under a foundation during backfilling

<table>
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<tr>
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<tbody>
<tr>
<td>2</td>
<td>0.75</td>
<td>0.0</td>
<td>0.0</td>
<td>2.2</td>
<td>2.1</td>
<td>2.5</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>0.95</td>
<td>1.3</td>
<td>5.2</td>
<td>3.7</td>
<td>4.4</td>
<td>2.1</td>
<td>5.8</td>
</tr>
<tr>
<td>4</td>
<td>1.15</td>
<td>1.5</td>
<td>8.3</td>
<td>5.5</td>
<td>4.9</td>
<td>3.0</td>
<td>8.6</td>
</tr>
<tr>
<td>5</td>
<td>1.35</td>
<td>0.0</td>
<td>7.1</td>
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<td>3.4</td>
<td>12.6</td>
</tr>
<tr>
<td>6</td>
<td>1.60</td>
<td>4.4</td>
<td>18.6</td>
<td>17.4</td>
<td>9.9</td>
<td>6.3</td>
<td>21.9</td>
</tr>
<tr>
<td>7</td>
<td>1.85</td>
<td>0.0</td>
<td>18.6</td>
<td>15.3</td>
<td>9.2</td>
<td>6.4</td>
<td>21.8</td>
</tr>
</tbody>
</table>

Note: 1Ps, 2Ps and 1Ps, 2Pb pressure meters measure the stress directly under the foundation

Fig. 5. Vertical displacement of the structure key after backfilling
Table 2 presents the summary of the recorded values of vertical displacement of the structure key due to the application of three cycles of standard loads.

The graph in Figure 6 presents a comparative analysis of the stress values under a reinforced concrete foundation and under a steel sheet foundation recorded after applying a soil backfill (without load), and during the successive application of standard loads (OBC1 – OBC3).

Figure 7 presents a chart with a comparison of the structure key displacement values for both structures, recorded at the application of the respective standard loads.

Table 2. Vertical displacement of the structure key under the three cycles of applying standard loads

<table>
<thead>
<tr>
<th>Type of applied load</th>
<th>Structure on a steel foundation [mm]</th>
<th>Structure on a reinforced concrete foundation [mm]</th>
</tr>
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<tbody>
<tr>
<td>OBC1 standard</td>
<td>–4.27</td>
<td>–4.12</td>
</tr>
<tr>
<td>OBC2 standard</td>
<td>–4.81</td>
<td>–4.69</td>
</tr>
<tr>
<td>OBC3 standard</td>
<td>–5.16</td>
<td>–5.00</td>
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</table>

Fig. 6. Comparison of the stress values under a reinforced concrete foundation and a steel sheet foundation recorded after making a soil backfill (without load), and during the successive application of standard loads.
The results show that the backfilling of the structure situated on a flexible foundation demonstrated that the test model developed for the purposes of the study is correct. This holds true for the values of stress under the foundation, as well as for the horizontal displacement and vertical displacement of the key of the steel shell, i.e. the increase of its elevation, which is a typical phenomenon in buried shell structures.

The study revealed the conformity of the values of the vertical displacement of the structures developed (under the successive standard loads) for the analyzed structures based on a reinforced concrete ("massive") foundation and a flexible foundation made of corrugated steel sheet. It should be noted at this point that the measured values of the vertical displacement of the key of the steel shell are minor for both foundation types.

A similar conformity was also observed for other analyzed parameters, such as horizontal displacement recorded for both foundation types.

The analysis of the results also showed that the stress values in the soil under the steel foundation (both during backfilling the shell and under the successive standard loads) are lower than those recorded under the reinforced concrete foundation.

To summaries, the obtained results demonstrate complete conformity of both models based on the rigid and flexible foundations (the minute differences recorded during the tests do not have any “significant” impact on the behavior of the structure during its operation).
In terms of practical applicability, the research carried out so far supports the claim that the trend recently observed in engineering practice, i.e. the use of flexible foundations made of corrugated sheet metal under buried flexible structures has no detrimental impact whatsoever on their behavior under use.

4. DEVELOPMENTAL TRENDS IN FOUNDATION OF SHELL STRUCTURES PRACTICE

The importance of the issues raised in this paper is corroborated by the widespread use of the referred structures in engineering practice relating to transport infrastructure, including not roads, but also railway structures.

The authors suggest that intensified analyses of such structures should be carried out as a follow-up. This will inevitably contribute to further optimization of buried shell structures, and consequently reduce the costs of infrastructure projects which take advantage of such solutions.

The authors also suggest that intensified analytical and numerical studies should be carried out for this foundation method. This will contribute to further optimization of buried shell structures, and consequently reduce the costs of infrastructure projects which take advantage of such solutions.

As proven by actual practice in other European countries and the USA, the technology of founding buried shell structures on flexible foundations is popular and widely used, in particular for difficult soil conditions. This solution is one of few that enable the erection of a structure merged with its foundations on the previously prepared subsoil (Fig. 8).

Fig. 8. Founding a structure with a corrugated sheet foundation on a previously prepared aggregate
On the basis of the results of the study, the authors claim that further studies should be attempted so as to establish, among others, a target range of flexible foundation types for general use by investors.

An adequate insight into this issue will make it possible to develop optimal and sustainable engineering solutions that will benefit both the environment and the users of transport lines, e.g. in the form of Recommendations for the Design, Construction and Maintenance of Buried Steel Shell Structures on Flexible Foundations (made of corrugated sheet) for general use in infrastructural civil engineering.

5. REMARKS AND CONCLUSIONS

1. Due to the increasing popularity of buried shell structures in infrastructural civil engineering, an effort should be made to gain the best possible insight into the behavior and characteristics of such structures. Therefore, it is crucial to investigate the proper way of making foundations for these structures.
2. Further research on optimum foundations, including flexible foundations, can provide substantial practical and economic advantages.
3. The authors claim that the standardization of such structures in terms of structural uniformity, i.e. the use of a flexible support structure and a flexible foundation, can be advantageous in the use of such facilities.
4. A comprehensive overview of outcomes related to the matter discussed in this paper should be carried out so as develop an optimal system of making foundations for such structures.
5. The next step according to the authors should involve the development of appropriate guidelines for the foundation of buried shell structures made of corrugated sheet metal, whose implementation in engineering practice would certainly help to improve the durability and economic efficiency of these facilities.

LITERATURE

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