Analysis on Mathematical Models for the Protection Solutions of a Major Sewage Collector

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Abstract. The infrastructure development can lead to circumstances in which new roads affect the existing underground public facilities, serving the neighbouring areas. In order to connect the A3 highway with a main road in Bucharest, a new junction arm is planned, crossing on top one of the major existing sewage collectors (a 3.5 m diameter cylindrical structure made of precast segments with interior lining). The paper presents the numerical analyses using 2D of two protection solutions suggested for the collector: (1) a reinforced concrete slab supported on bored piles; (2) a self-standing reinforced concrete arch calotte. Concurrently, a third solution suggested by the contractor was dismissed (protection using a corrugated metal arch structure with independent foundations). All the loading conditions were considered: earth fill and road structure weight, traffic and exceptional water pressure inside the collector. The results (expressed by the annular and sectional stresses) were compared to the collector’s strength capacity. Advantages and disadvantages of each solution were emphasized and design recommendations for the protection structures were made.

1. Introduction

The infrastructure development in large cities can lead to circumstances in which new roads affect the existing underground public facilities that are serving the neighbouring areas (water supply, sewerage, fuel pipelines, etc.). This paper presents a similar situation – the construction of a junction arm, which will connect a main boulevard in Bucharest with A3 highway affecting a main sewerage collector which is positioned under the new planned road. In order to protect the existing collector two protection solutions were analysed using finite element modelling.

There is a large number of studies based on the finite element method in which the authors tackle the soil-structure or structure to structure interaction, for example: P. Lueprasap et al. [1] analyse the interaction between metro tunnels and pile foundations; A. Yao, Z. Jiantaosi Z. Yijun [2] analyse the effect of a large excavation pit realised for a metro station on a near building founded on steel pile foundations, etc. Also, the analysis of buried pipes (especially steel pipes for fuel transport) subjected to accidental or unusual loadings from the surface level is an important research field: J. Zhang, Z. Liang and G. Zhao [3] analyse, using FEM, the effect of an overloading at the ground surface on buried pipes and the parameters which influence their resistance; Z. Xueshen, Y. Zeliag, H. Peng [4] analyse the stress state of a gas pipeline subjected to an overloading from a planned high-filling road works and suggests pipeline thickening as a protective measure.

Another important study of interest is “Guidelines for underground utility installations crossing highway rights-of-way” by Transportation Association of Canada [5]. This study manages the protective
measures for the existing underground public facilities networks and focuses on protections of buried pipes positioned near main roads.

The current paper starts with a short description of the existing and designed structures and continues with the analysis of the structural solutions considered for the collector’s protection. At the end, a series of advantages and disadvantages for each proposed solution are highlighted and pictures from the execution phase are presented.

2. Project overview

A3 is a highway under construction, which starts from Bucharest and will connect to M4 highway in Hungary. It will cross the Carpathians Mountains through Prahova Valley, will pass through Transylvania plateau along SE-NV direction and will reach Bors, a major border crossing point to Hungary. Since 2012, a small part of this road was finished – 55.5 km out of 62 km – which connects Bucharest to Ploiești – a segment between the ring roads of the two cities [6]. In order to finish this segment and connect it to Bucharest, the execution of a junction arm is required. This junction arm is designed to be executed, for almost 200 m, on top of a major sewerage collector (figure 1-a).

The collector is a 3.5 m diameter cylindrical structure made of precast segments with interior lining, finished in 1973 using semi-mechanized shield technology. The cylindrical section is made of 6 precast segments with variable thickness (a curve plate of 5 cm with perimeter ribs of 16 cm). The total thickness of the cylindric wall is 23.5 cm (figure 1-b) and is made of the segmental lining and a 7.5 cm of in-place secondary lining. The reinforcement scheme of the precast segments is as follows: 4Ø8 mm + 2Ø6 mm on extrados and 4Ø10 mm + 2Ø6 mm on intrados. For the in place secondary lining the reinforcement is made of 4Ø6 mm/m. The buried depth of the collector, measured from the keystone to the natural ground, is between 2.70 m and 3.60 m.

Figure 1. Plan view of the interaction area (a) and typical cross section with reinforcement scheme of the collector (b)

The analysis of the existing design drawings and the calculus performed to determine the collector’s strength capacity led to the conclusion that the structure was designed to undergo, at limit, the loadings from vertical and lateral earth pressure and from exceptional internal hydraulic pressure. However, its structural capacity reserves are not enough to support the additional loads from the highway (technological and traffic). Thus, it was decided to protect the existing structure by additional structural components. The paper presents the analysis carried out and some considerations for the following protection solutions:

- Option 1 - a reinforced concrete slab supported on bored piles;
- Option 2 - a self-standing reinforced concrete arch calotte.

Concurrently, a third solution suggested by the general contractor was dismissed (protection using a corrugated metal arch structure with independent foundations) because it does not provide the desired resistance to internal hydraulic pressure.
3. Numerical modelling

In order to assess the protection solutions, finite element models were used. The numerical analysis was done for 4 different cross sections by 2D plain strain modelling (the constant collector’s diameter being small compared to the length of the interaction area). They were selected based on the earthfill thickness between the road level and the collector’s keystone and also based on the relative road – collector position. These 2 parameters lead to different loading schemes, presented in figures 1 and 2.

For both protection options, the analysis was done using 2 types of models:

- One, in which the structural components were modelled using 2D structural solid elements. For these models the sectional efforts (bending moment and shear force) were determined by unitary effort integration.

- Another, in which the structural components were modelled using 2D elastic beam elements. The beam properties were selected in accordance with the real geometry of the modelled structure. For these models the diagrams were available in a direct manner.

For all models the terrain was meshed using solid elements with incompatible modes. The material properties assigned for each component are presented in table 1. The loads taken into account were: the self-weight for the earth mass and the structural components, the traffic load and the hydrostatic pressure inside the collector (exceptional loading). Traffic was modelled as a uniform pressure of 40 kN/m² distributed on 2 lanes (6 m). Concerning the collector’s resistance against internal pressure, the adopted value corresponds to a water column, which reaches the ground surface (the burial depth for each section being shown in figure 2).

| Material            | $M_{2,3}$ [kPa] | $M_0$ [kPa] | $E$ [kPa] | $\gamma$ (kN/m³) | $\mu$ | Model colour |
|---------------------|----------------|-------------|-----------|------------------|------|--------------|
| 1 Silty clay        | 7100           | 1.3         | 9230      | 18.3             | 0.35 | Green        |
| 2 Sandy silt        | 10900          | 1.5         | 16350     | 18.5             | 0.35 | Blue         |
| 3 Sand              | 8000           | 1           | 8000      | 19               | 0.30 | Red          |
| 4 Compacted filling | 20000          | 1           | 20000     | 20               | 0.32 | Yellow       |
| 5 Road foundation   | 35000          | 1           | 35000     | 20               | 0.32 | Purple       |
| 6 Concrete structures | 2.5E07     | 25          | 25        | 0.20             |      | Purple       |

The numerical analysis for each model is divided into 8 calculation steps, to emphasize the evolution of the stress - strain state. The simulation of the execution technology was made by elements’ activation and deactivation, in subsequent load steps.

The main goal of the analysis is to determine the bending moments, shear force and axial force diagrams in all structural components (collector and protection solutions). For the collector’s structure the results were compared to its strength capacity, while for the protection structures, the results were used for preliminary design.
3.1. Solution no. 1 - Reinforced concrete slab supported on bored piles

The first analysed solution is designed as a buried frame positioned around the collector. It is made of concrete piles interlocked in longitudinal direction with beams and a horizontal reinforced concrete slab. Two of the models realized for this solution are presented in figure 3: a 2D model for section no. 2 and an additional 3D model used for establishing the optimal distance between piles.

Figure 3. Mathematical models for variant no. 1 - a. 2D model for section 2; b. 3D model and structural elements detail

The main steps used in the analysis are:

- step 1. in situ analysis (the simulation of the initial stress state in the soil mass);
- step 2. collector's execution (the simulation of the initial stress state in the structure);
- step 3. bored piles execution;
- step 4. excavation process up to the slab’s intrados;
- step 5. reinforced concrete slab execution;
- step 6. filling process for natural terrain restoration;
- step 7. highway foundation execution and traffic loads;
- step 8. internal hydrostatic pressure inside the collector.

The results for this solution are presented in the following figures: the annular stresses and diagrams for bending moments, shear force and axial force in figure 4 and position of N, S, E, V points on axial force - bending moment interaction curves in figure 5. It can be noticed that, for the reinforced concrete slab supported on bored piles, all the considered points for collector analysis are positioned inside the interaction curves for all the loading conditions (figure 5 – green points).

Figure 4. Results for the collector’s structure - step 7
For the reinforced concrete slab, the bending moment and shear force diagrams show a static scheme of a simple beam on two supports due to the limited torsion stiffness of the longitudinal beams. The final design for this solution led to the following configuration:

- The distance between the bored piles is 3.0 m, placed at a distance of 1.0 m from the collector. The pile diameter was chosen of 600 mm and its length roughly 12 m under the slab level.
- The cross section for the longitudinal beams was chosen in order to accommodate the technological deviations and to offer a proper bending stiffness – 70 x 100 cm.
- The protection slab is placed at approximate 1.0 m above the collector’s keystone and its thickness of 50 cm was chosen in order to provide a proper bending stiffness and to limit the reinforcement amount.

3.2. Solution no. 2 - a self-standing reinforced concrete arch calotte

The second protection solution consists in a self-supported reinforced concrete structure, as an arch calotte with variable cross section, executed on top of the collector. The 2D models and the numerical simulation for this solution are presented in figures 6 (the one build for section 1) and 7:

- step 1. in situ analysis (the simulation of the initial stress state in the soil mass);
- step 2. collector's execution (the simulation of the initial stress state in the structure);
- step 3. simulation of the excavation above the collector;
- step 4. placing of the neoprene separation layer;
- step 5. execution of the arch calotte;
- step 6. filling process for natural terrain restoration;
- step 7. highway foundation execution and traffic loads;
- step 8. internal hydrostatic pressure inside the collector.

Figure 5. Results for variant no.1: a) step 7; b) step 8

Figure 6. Mathematical model for variant no. 2 (section 1) – calculation step 8
Results on preliminary models showed that this solution can work only if a structural separation between the 2 structures is ensured. This was observed after the modelling of 2 extreme cases: (A) independent displacements on radial and annular directions at the interface, due to the neoprene layer, and (B), coupled displacements on radial and annular direction at the interface. The results showed different distributions for the principal stresses in the collector’s structure (figure 8):

A. the distribution of principal stresses shows that both the collector and the protection are in an eccentric compression state, with their own tension and compression regions;
B. the 2 structures work like a single one, the collector’s area being in an eccentric tension state, its bending moment capacity becoming negligible.

This separation layer must allow the relative sliding at the interface between the two structures and also to provide a sufficient axial stiffness to constrain the collector’s radial displacements by the calotte effect, in case of increased internal pressure. This separation was modelled using step 4 – the activation of a 2 cm thick neoprene layer with the following properties: $\rho = 15$ kN/m$^3$, $E = 4000$ kPa, $\mu = 0.35$.

The results for this protection solution are presented for step 7 in figure 9 (results for section 1). For the calotte structure, the bending moment, shear force and axial force diagrams show a static scheme close to one of a simple arch on two supports.
Last step’s results for the collector’s structure are presented in figure 10. It can be noticed that most of the N-M pairs for the analysed points are situated inside the interaction curves. However, for section no. 3, the N-M pairs for the N and S points are situated outside. Based on this finding, the initial situation was analysed (without protection or highway works) and it was found that for the exceptional loading case, the same points are situated outside the curves. Even though, the collector worked without any incidents for many years, being occasionally subjected to exceptional hydrostatic pressure. Anyway, from the graphical representations (figure 10), it can be observed that the calotte protection variant offers a higher safety factor than the initial situation and to be on the safe side it was suggested an increased thickness for the section no. 3 zone.

Figure 9. Results for the collector and the protection arch calotte (step 7)

Figure 10. Results for collector’s structure– hydrostatic pressure exceptional loading – step 8
3.3. Dismissed solution – protection using a corrugated metal arch structure with independent foundations

This solution was suggested by the general contractor and it assumes the collector protection by erecting prefabricated corrugated metal arch elements (Multiplate MP200-VA50), to transfer the vertical loadings down to independent foundations.

For this solution, the results on the dedicated model show that the protection of the collector against exceptional loading (hydrostatic pressure) was not ensured. An important part of the collector’s ability to withstand internal water pressure is offered by the weight of the terrain situated on top of the collector. The suggested solution solves the additional loadings from the highway structure but makes the collector vulnerable to hydrostatic loading by removing the ground stabilizing layer situated on top of the collector.

![Figure 11. Variant 3–mathematical model - step 6](image)

The finite element model used for this solution is based on a typical cross section and has the same properties as the previous ones (figure 11). The value for the hydrostatic pressure corresponds to a water column of 3.5 m from the collector’s keystone. The adopted calculation steps are:

- step 1. in situ analysis (the simulation of the initial stress state in the soil mass);
- step 2. collector’s execution (the simulation of the initial stress state in the structure);
- step 3. simulation of the excavation above the collector;
- step 4. erection of the protection structure and its foundations;
- step 5. filling process for natural terrain restoration and highway foundation execution;
- step 6. traffic loads and internal hydrostatic pressure in the collector.

The results for the collector’s structure are presented in figure 12(a) – step 2 the upper diagrams and step 6 the lower ones. When the collector is subjected to water pressure, the axial forces are negative and the N-M pairs for all the chosen points are situated outside the graph, thus the resistance of the collector is not ensured (figure 12(b)).
4. Recommendations for choosing the optimal variant

The 2 protection solutions which were suggested have been analysed taking into account both the results from mathematical modelling and their advantages/disadvantages. The most important factors were: ensuring the protection of the collector, the execution technology, the amount of civil engineering works and the presence of civil works in the collector’s vicinity.

A summary of pros and cons for the first solution – a reinforced concrete slab supported on bored piles:

- Advantage: offers a better protection than the second option
- Advantage: there is no need for stripping the collector or for other construction works near it
- Disadvantage: greater usage of materials, equipment and workmanship, thus a higher price
- Disadvantage: longer execution period

A summary of pros and cons for the second solution – a self-standing reinforced concrete arch calotte:

- Advantage: the most economical solution
- Advantage: simple and fast execution, without hidden construction works
- Disadvantage: need for stripping the collector and also for construction works in its close vicinity
- Disadvantage: need of ensuring structural separation of the 2 structures
- Disadvantage: offers a lower level of protection when compared to the first option, but at the same time does not endanger the structure of the collector

In the end, the chosen solution by the general contractor was the second one. Figures 13, 14 and 15 show images during execution. The construction works were finalized without incidents.
Figure 13. Test excavations over the collector

Figure 14. Neoprene coating
5. Conclusions
This article presents the analyses carried out in order to offer criteria for the selection of the final protection solution of a main sewerage collector. 2D models were created to study the following protection options: (1) a reinforced concrete slab supported on bored piles and (2) a self-standing reinforced concrete arch calotte. In addition, a third option that has been suggested by the general contractor (protection using a corrugated metal arch structure with independent foundations), was rejected due to the fact that it did not ensure the structural resistance of the collector under internal hydrostatic pressure. In the end, the second solution was the chosen by the general contractor, since it provided the desired safety factor and also a cheaper and faster execution.

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