Numerical Study of the Use of Tyre-Derived-Aggregate (TDA) as the Backfill Above Flexible PVC Pipeline

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Abstract. Tyre Derived Aggregates (TDA), produced by shredding scrap car tyres, show many interesting features, such as: durability, low bulk density, thermal insulation, good drainage properties or ability to damp vibrations, which makes them a useful material for civil engineering. One of the possible applications is the partial filling of excavations with TDA during the construction of underground pipelines in order to decrease the load applied on the pipe. The article presents results of a multivariate numerical study of 2D FEM models of a flexible PVC pipe - soil system, in which the presence of a mixture of sand and TDA (tyre chips - 40% by weight) (STCh) in the backfill was simulated. The models differed in the thickness of the STCh layer \( t = 0 – 0.9 \) m and inclination of the excavation walls (a trench with vertical walls or open excavations with 3:1 and 1:1 slopes). The main goal of the numerical analyses, performed by means of the Z_Soil.PC program, were to investigate the effect of the presence of the softer STCh layer in the backfill zone on the pipe deformation (relative deflection \( \delta/D \)) and internal forces in the pipe wall. The soil was simulated with the use of either the Hardening Soil Small (HSS) or Coulomb-Mohr (CM) constitutive model with the parameters’ values estimated based on results of laboratory tests published by researchers from Wollongong University). The PVC pipe was modelled as linear elastic. The results of the analyses show that, due to enhanced arching, STCh layer of the optimum thickness \( t = 0.55 \) m can effectively reduce \( \delta/D \) when used in the backfill of the trench. It can also decrease the difference between the maximum and minimum bending moment in the pipe wall, leading to less ovalization of the pipe cross-section. This positive effect diminishes if the width of excavation is larger, as the model is gradually transforming towards the positive projecting conduit type. The CM model gives underestimated values of the pipe deformation and internal forces. Though, in the case of lack of all the HSS parameters’ values, it is better to use the CM model with \( E = E_{50} \) than \( E = E_{ur} \) as it gives a better approximation of pipe behaviour.

1. Introduction
The number of car tyres produced in Europe is equal to about 4,7 million tons/year [1]. On average, after 10 years of use, each passenger car tyre should be replaced for safety reasons. This means that it ends up as a waste – a waste that cannot be simply thrown into the trash as, after the introduction of European Union’s Directive 1999/31/EC ‘on the landfill of waste’, it is prohibited to landfill whole or shredded scrap tyres. The European nations are now collecting and treating 92% of the end-of-life tyres they generate, out of which 6% is retreaded, 12% reused or exported, 28% go for energy recovery (they are burnt e.g. in cement kilns) and 46% for material recovery [2]. Unfortunately, the material recovery in Europe means mostly using the granulated rubber in sports or playground mats, and very rarely the whole or shredded scrap tyres are used in civil engineering projects. This is unfortunate, as this material,
called tyre derived aggregate (TDA), shows many interesting features from the engineering point of view – it is durable, lightweight (0.5 – 1.0 tons/m³ [3]), has excellent thermal insulation (8 times more insulating than gravel), drainage (permeability greater than 1 cm/s) and vibration damping properties. Most of the civil engineering applications: embankment fills, retaining wall backfills, landslide repairs, vibration damping, septic leach field drainage layers, leachate and gas collection layers in landfills [4] have been realized in the USA and only a few in EU (including just one in Poland [5]). The main reason for that is most probably the lack of legislation - there is no valid European standard regulating the civil engineering applications of scrap tyres, like the ASTM D6270 [6] in the USA, thus people do not want to take the risk and utilize the material that is new to them. The situation may change if more research results are published, showing the characteristics of scrap tyres, together with the benefits and limitations of their use.

The article presents one of the possibilities of the use of TDA in civil engineering: as a load-reducing layer made of a mixture of sand and TDA (STCh) in underground pipe backfill. This issue was considered in relation to flexible PVC pipes. They are widely used for the construction of sewage and water supply systems, as a solution that is durable and ensures long-term (at least 50 years) safe functioning. A characteristic feature of flexible pipes is their ability to deform and interact with the ground during load transfer (pipe-ground system). This interaction depends on the relationship between the stiffness of the pipe and the surrounding soil. Therefore, not only the material parameters of the pipe (especially the circumferential stiffness), but also the parameters of the soil backfill, which in this case becomes a structural element, are important in the safe transfer of external loads. The deformation of the pipe, caused by the weight of the overburden and possible surface load, occurs with the simultaneous activation of the lateral soil zones. As the deformation increases, the horizontal soil resistance changes from ‘at rest’ (earth pressure coefficient \( K < 1 \)) to passive \( (K > 1) \). The pipe wall is then compressed and bent. Bending is the greater, the greater the difference between the vertical and horizontal load. Theoretically, under certain conditions, vertical and horizontal pressure may equalize \( (K = 1) \) and, as a consequence, the pipe would only be subject to circumferential compression, which is the most favourable case [7].

In the case of buried flexible pipes, the phenomenon of arching (so-called positive arching) is particularly important. It consists in the fact that the soil column above the pipe has a relatively small possibility of movement, due to the action of friction forces at the contact with the adjacent columns, thanks to which the load acting on the pipe gets reduced. An enhancement of this effect can be achieved if the fill material above the pipe is relatively softer than the natural soil at the sides of the pipe. Instead of simply using the natural, but less compacted, material (only if it is coarse grained) to create the compressible zone above the pipe, other materials may be utilized, like polystyrene ([8], [9]) or some waste materials: straw bales ([8], [10]), tree leaves [11], sawdust or wood chips [12]. TDA layer (e.g. tyre chips) or a mixture of soil with TDA (e.g. sand and tyre chips – STCh) can be used for this purpose as well ([13], [14]). The use of the latter is a sustainable (material recovery of scrap tyres instead of their incineration and emission of toxic smokes into the atmosphere), durable (especially when compared to leaves, sawdust or straw) and cost effective (compared to EPS) solution.

Relative deflection (relative deformation), defined as the ratio of the change in the vertical diameter of the pipe (pipe deflection) \( \delta \) to its diameter \( D \) expressed as a percentage is the best parameter to characterize the deformation of a flexible pipe in the ground. The pipe deflection \( \delta \) can be determined based on the Spangler formula [15] or its many modified versions used in the European standards. The \( \delta \) depends on the value of the vertical load, circumferential stiffness of the pipe and soil stiffness. Relative deflection \( (\delta/D) \) is the basic criterion for dimensioning pipes. Usually, the permissible relative deflection for plastic pipes does not exceed 2.5 – 6% [7].
In Poland, there are two analytical methods: German ATV and Scandinavian VAV 70, that are commonly used to determine the relative deflection and strength of typical underground thermoplastic pipes. The ATV method [16] allows checking e.g. stress and deformation state conditions and stability. Several factors, such as: the soil conditions, the types of communication loads, the conditions of pipe installation and the shape of excavation are taken into account in the calculations. This method is not easy to use, as it requires determination of the precise values of numerous coefficients. The VAV 70 method (also called the Molin’s method) [17] is more often used and it is recommended mainly for strength calculations of thermoplastic pipes with diameters up to 500 mm. The value of the final long-term relative deflection of the pipe, determined according to this method, is influenced by the operating loads, installation conditions and the quality of the ground below the pipe.

Alternative to the analytical methods are undoubtedly numerical ones, e.g. the finite element method (FEM), which can take into account not only any unusual geometric outline of a given case, but also gives an opportunity to analyse various options of material characteristics, loads, technological processes of pipe assembly, etc. Especially important in the case of the flexible pipe-ground systems is the ability of the FEM calculations to simulate the 2D or 3D interaction of the deformed pipe and the ground [18]. In the numerical analyses, the PVC pipe material is usually modelled as linear elastic, whereas the soil behaviour can be simulated by means of a wide range of constitutive models – from the most commonly used elastic-ideally-plastic Coulomb-Mohr model (CM) to more advanced models, e.g. the elastic-plastic model with isotropic hardening Hardening Soil Small (HSS). The HSS model definitely better simulates the complex macroscopic effects occurring in monotonically or cyclically loaded soils, such as densification, loading history, plastic flow, dependence of soil stiffness on the state of effective stress or dilatancy. It takes also into account the strong nonlinearity of the soil stiffness in the very small strain range (hyperbolic Hardin-Drnevich relation) – a phenomenon, which is very important in the soil-structure interaction problems and not represented at all in the simple elastic-plastic models.

Below presented are the assumptions and results of numerical analyses of 2D models of PVC pipe-ground systems, conducted with the use of the HSS and CM constitutive models. In the backfill, a layer of sand-TDA mixture (STCh) was included in order to estimate the effect of such an inclusion on the deformation and state of stress in the pipe wall.

2. Numerical models

2.1. General description

Three different numerical FEM models were built in the ZSoil.PC program, representing a buried pipe of a unit length in a plane strain condition. The total depth and width of the models are: \(H = 3.5\) m and \(L = 6.0\) m, respectively (figure 1). Three different material zones were introduced, called: native soil, backfill and STCh. In each model, an excavation 2.2 m deep and 1.1 m wide at the bottom was simulated. The excavation was filled with the backfill material. The backfill zone contained two inclusions. The first inclusion was a PVC pipe (modelled as a beam) – 500 mm in external diameter \(D\), having the wall thickness of \(s = 0.0123\) m. Its culvert was located 20 cm above the bottom of the excavation. Starting 30 cm above the pipe crown, occurred the second inclusion: a sand-tyre chips layer (STCh) of thickness \(t\). In terms of the geometric layout, 15 different models were created – they differed by the slope of the excavation walls and the thickness of the STCh layer. In the model N (narrow) the excavation was a narrow trench with vertical walls, while in models M (medium) and W (wide) the walls of the trench were inclined by a ratio of 3:1 and 1:1, respectively – see figure 1. The thickness of the STCh layer was equal to \(t = 0.9\) m, 0.7 m, 0.55 m, 0.4 m or 0.0 m (no STCh in the latter case). Identical boundary conditions have been introduced in all the models: roller supports at the vertical edge nodes and pin supports at the bottom edge. An evenly distributed load of intensity \(q = 300\) kPa was introduced on the upper edge of the models, which might represent e.g. a high embankment.
2.2. Constitutive models and parameters values

In the basic calculation variant, the native soil, backfill and STCh layer were modelled with the use of the HSS model. The material parameters of the native soil, corresponding to a very dense, well-graded, angular sand, were generated using the parameters’ database of the ZSoil program. The parameters of the backfill and the STCh layer were adopted on the basis of the results of actual laboratory tests. The backfill parameters represented poorly graded sand (the maximum size of the smallest 50% of the sample $D_{50} = 0.35 \text{ mm}$, coefficient of uniformity $C_U = 1.58$, relative density $D_r = 50\%$) and the STCh layer – a mixture of this sand with 40% (by weight) of scrap tyre chips (rectangular pieces of uniform thickness of about 6 mm; the maximum width and length not exceeding 8 and 22 mm, respectively). The values of the backfill and STCh parameters for the HSS model were estimated based on results of monotonic and cyclic triaxial tests, measurements of shear wave velocity and direct shear tests, conducted by the researchers of Wollongong University in Australia ([19], [20], [21], [22]). The Poisson ratio $\nu$ was assumed as equal to 0.25, based on [23]. The values of the selected material parameters of soil zones and the STCh layer are summarized in table 1.

The PVC pipe material was modelled as linear elastic with the (long-term) Young modulus $E = 3200 \text{ MPa}$, bulk weight $\gamma = 14.0 \text{ kN/m}^3$, Poisson ratio $\nu = 0.4$ [24].

The numerical calculations of all the variants (models N, M and W with different STCh layer thicknesses) were additionally conducted in the option of the native soil, backfill and STCh layer described by means of the CM model. The parameters of the CM model were obtained by adopting some parameters of the HSS model (see table 1). The HSS model requires estimation of three values of the Young modulus: initial $E_0$ based on shear wave velocity, secant $E_{50}$ – representing the soil stiffness at 50% of deviatoric stress at failure and $E_{ur}$ – representing soil stiffness in unloading reloading test. It is
not obvious which out of the two: \(E_{50}\) or \(E_{\text{Eur}}\) should be used in the CM model, that is why both the versions were taken into account (they were further called CM-E50 and CM-Eur, respectively).

The following convention of naming all the cases (models) was adopted: the thickness of STCh layer/type of excavation/constitutive model, so e.g. model 0.4/N/HSS is a model with the narrow vertical walls excavation, 0.4 m thick STCh layer and soil layers modelled using the HSS model; whereas the 0/W/CM-Eur model means the case with the wide 1:1 slope excavation, without the STCh layer and soil layers modelled using the CM model with the Young modulus value \(E = E_{\text{Eur}}\) from table 1; etc.

### Table 1. Material parameters of native soil, backfill and STCh layer - model HSS

| Parameter                              | Used also in the CM model? | Symbol | Unit     | Native soil | Backfill | STCh   |
|----------------------------------------|----------------------------|--------|----------|-------------|----------|--------|
| Young modulus in unloading/reloading at ref. stress | Yes (only in CM-Eur) | \(E_{\text{ref}}^{\sigma_{\text{ref}}}\) | kN/m²     | 240 000*   | 47 430**) | 24 490 |
| Secant Young \(E\) modulus at 50% of deviatoric stress at failure \((q_{f})\) | Yes (only in CM-E50) | \(E_{50}^{\sigma_{\text{ref}}}\) | kN/m²     | 60 000     | 25 263   | 3 981  |
| Initial Young modulus at ref. stress   | No                         | \(E_{0}^{\sigma_{\text{ref}}}\) | kN/m²     | 515 147    | 186 383   | 66 073 |
| Friction angle                         | Yes                        | \(\Phi\) | °        | 43.1       | 39.7     | 35.9   |
| Dilatancy angle                        | Yes                        | \(\Psi\) | °        | 11.6       | 22.0     | 5.0    |
| Cohesion                               | Yes                        | \(c\) | kN/m²    | 1.0        | 3.3      | 20.1   |
| Unit weight                            | Yes                        | \(\gamma\) | kN/m³   | 16.9       | 15.8     | 12.5   |
| Oedometric tangent modulus             | No                         | \(E_{\text{oed}}\) | kN/m²    | 60 000     | 20 394   | 3 807  |
| Hardening parameter                    | No                         | \(H\) | kN/m²    | 36310.2    | 20477.1  | 3000.83 |
| Hardening parameter                    | No                         | \(M\) | -        | 1.73681    | 1.58221  | 1.60874 |

*) reference stress for Young modulus \(\sigma_{\text{ref}} = 100 [\text{kN/m²}]\)

**) reference stress for Young modulus \(\sigma_{\text{ref}} = 69 [\text{kN/m²}]\)

### 3. Results and discussion

The results of the numerical calculations were analysed in terms of the influence of the STCh layer of varying thickness on the distribution of vertical stresses in the ground, pipe deformation and internal forces in the pipe wall – i.e. circumferential bending moment \(M_z\) and circumferential normal force \(N_x\).

#### 3.1. Influence of STCh layer on vertical stress in the ground

The introduction of the STCh layer results in a change in the vertical stress distribution in the ground, which is well expressed by the value of vertical stress directly above the pipe crown (figure 2).

The beneficial effect of the STCh layer is clearly visible in the case of the narrow excavation (model N): the vertical stress in the soil, when the STCh layer 55 cm thick is present in the backfill zone, is reduced by about 22% for HSS model and by 25% for CM-E50 model. A significantly lower reduction of only 4% was demonstrated for the CM-Eur model. In the case of the excavation of medium width (model M), the reducing effect of the STCh layer is lower (7%) and occurs only for HSS and CM-E50 models. In the case of the wide excavation (model W), no positive impact of STCh was observed – contrary, the vertical stress turned out to be greater than in the case without the STCh layer \((t = 0)\). This must be related to the change in the nature of the pipe-soil interaction as the excavation width increases.
The increase of the STCh layer thickness (above 40 cm) has practically no influence on the distribution of vertical stress. However, the impact of the choice of constitutive model is significant. The values of the vertical stresses determined using the HSS model are higher than the values determined using the CM model, with $E = E_{50}$ giving results closer to the HSS model.

3.2. Influence of STCh layer on PVC pipe deformation

The exemplary modes of ground and pipe deformation – for 0/N/HSS and 0.4/N/HSS model – together with the maps of vertical displacements in the ground at $q = 300$ kPa are shown in figure 3. It is clear that in the 0.4/N/HSS model the STCh layer ‘takes over’ the ground deformation observed at the surface and so effectively reduces the backfill deformation around the pipe. The pipe gets less ovalized when compared to the model without the STCh layer.

![Figure 2. Diagram of the vertical stress above the pipe crown depending on STCh layer thickness](image)

The impact of introducing the STCh layer of varying thickness on the relative deflection of the pipe is shown in figure 4. To check what is the optimum $t$, additional thicknesses between 0 and 0.4 m ($t = 0.2$ m and 0.3 m) were analysed with the HSS model. In the case of the narrow excavation and the constitutive model HSS, the beneficial effect of the introduction of the STCh layer over the pipe is clearly visible – it gives 40% reduction of $\delta/D$ at the optimum thickness $t = 55$ cm. If the soil and STCh are modelled with the use of the CM model the obtained reduction is smaller: by 30% or by 6% if $E = E_{50}$ or $E = E_{\text{Eu}}$, respectively. Increasing the thickness of the STCh layer over 55 cm does not bring any additional improvement. With the wider trench (M), the maximum reduction in relative deflection is much smaller: by 14% in the 0.4/M/HSS model, and increasing the thickness of the STCh layer over 55 cm can completely eliminate this effect. On the other hand, the use of the STCh layer in the wide excavation (W model) increases the relative deformation of the pipe (no matter what constitutive model is used), which means that the use of the relieving STCh layer above the pipe does not make sense in the cases, where the arching effect cannot occur.
Figure 3. Maps of vertical displacements (deformed mesh): a) model 0/N/HSS, b) model 0.4/N/HSS

Figure 4. Relative vertical pipe deformation depending on the thickness of STCh layer
3.3. Influence of STCh layer on internal forces in the PVC pipe wall

An exemplary distribution of circumferential bending moment $M_z$ and circumferential normal force $N_x$ for the 0.4/N/HSS model are shown in figure 5. The values of $M_z$ moments change sign—they are positive in the crown and culvert of the pipe and negative at the springlines. The values of $N_x$ forces on the entire perimeter of the pipe are negative (compressive) and uneven: the minimum occurs at the pipe crown and the maximum—at the springlines.

This mode of distribution in the other models is the same. However, there are significant differences in terms of the values of bending moments and normal forces depending on the width of the trench, the thickness of the STCh layer and the constitutive model used. The influence of the excavation width on the internal forces for models 0.4/N/HSS, 0.4/M/HSS, 0.4/W/HSS is shown for example in figure 6. The difference between the extreme values of $M_z$ and $N_x$ increases as the width of the excavation (and the size of the haunch area in the vicinity of the pipe) increase, meaning an increased risk of pipe ovalization.

![Figure 5. Bending moment $M_z$ and normal force $N_x$: model 0.4/N/HSS](image)

![Figure 6. Bending moment $M_z$ and normal force $N_x$ depending on the excavation’s width: models 0.4/HSS](image)

The maximum and minimum values of $M_z$ and $N_x$ against the thickness of the STCh layer for all the analysed cases are presented in figure 7. Based on this figure, it may be concluded, again, that the choice of the constitutive model significantly affects the observed values of $M_z$ and $N_x$. The greatest difference between the extreme bending moments $M_z$ was obtained for wide excavation and HSS model, the lowest for narrow excavation and CM-Eur model. This tendency is less pronounced in the case of $N_x$ forces. Just like presented above, the effect of the STCh layer thickness is negligible for $t > 0.55$ m.
4. Conclusions
The results of the numerical analyses of 2D models of the PVC pipe-soil system, taking into account the occurrence of STCh layer of varying thickness in the backfill zone and modelling of soil layers with the use of two various constitutive models allow the formulation of the following conclusions.

- An introduction of a compressible STCh layer in a backfill zone can effectively reduce the vertical stress applied on a buried pipe, leading to a decrease in relative deflection and internal forces in the pipe wall.
- This beneficial effect depends on the width of the excavation – the best result may be obtained if the pipe is located in a possibly narrow trench (with vertical walls). Larger trench widths, for which the width of the haunch zone is greater, change the nature of the PVC pipe-soil interaction: due to the lack of positive arching effect, the pipe may deform (ovalize) even more than without the STCh layer.
- It seems that the optimum in the analysed cases is the thickness of STCh layer $t = 0.55$ m. Further increase of the thickness has either no or detrimental effect on the effectiveness of this solution.
- It is obvious that the quality of a numerical analysis depends on the quality of the constitutive model and on the fact how close the parameter values represent the true soil behaviour. The use of elastic-plastic HSS model, which is able to represent more aspects of soil behaviour (e.g. nonlinearity of stiffness at small strains) than the simplest elastic-perfectly plastic CM model, resulted in obtaining higher value of stress in the soil above the pipe crown, higher difference in the extreme bending moments in the pipe wall and higher relative vertical pipe deformation than in the case of the CM model. The results of the CM models were closer to the ones obtained with the use of the HSS model if the smaller value of the Young modulus was applied ($E = E_{50}$ instead of $E_{50}$). It may be concluded that the use of the CM model in the analysis of flexible pipe-soil systems should be avoided as it may result in underestimating the pipe effort and deformation.

It should be emphasized that the above remarks were formulated on the basis of the specific cases of the PVC pipe-soil system. Generalization of these conclusions will be possible after their verification in laboratory or field experiments. An analysis of other types of native soils and backfill, as well as pipes with different wall thicknesses (different circumferential stiffness), would also be necessary.
Nevertheless, in our opinion, the fact that TDA (alone or mixed with sand) makes a valuable material to be used as an inclusion in the backfill above the flexible pipe in narrow trench technology has been proven. It results from its low unit weight and low stiffness. Taking into account that TDA is a durable, stable and environmentally sustainable material it may be treated as superior when compared to other lightweight materials used in a similar way, such as polystyrene, straw bales or wooden chips.

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