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TECHNICAL PAPER

Stability and Settlement Analysis of a Lightweight Embankment Filled with Waste Tyre Bales over Soft Ground

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Abstract

The waste tyre-derived products, including whole tyres, tyre bales, shreds, chips, and crumb rubber, have begun to be used in various geotechnical applications. In particular, the use of tyre bales in the construction of a lightweight embankment on the soft ground has the potential to satisfy the demand for low-cost materials exhibiting such beneficial properties. This paper presents the comparison between the common medium sand-filled embankment and two tyre-baled structures with various granular interlayers: medium sand and rubber aggregate. To assess the efficiency of tyre bale application in soft ground conditions, two subsoils were considered in the study: sandy clay and silty clay. The stability and settlement analysis of embankments, as well as subsoil bearing capacity checking, were performed for all structural cases. Bishop's limit equilibrium slicing method and the finite element method were used in the embankment and subsoil analysis. The comprehensive testing of tyre bales and filling materials was also carried out to obtain the set of parameters used in both analyses. The comparison allowed qualitatively assessing the effectiveness of using waste tyre bales as a filling of road embankment when founded on soft ground. The analysis revealed that the application of tyre bales generally enhanced the embankment stability, effectively reduced the embankment settlement, and reduced the normal stress in the subsoil. In the tyre-baled embankments, the slip surface is located mostly within the embankment slope, showing good rotational stability, independent of subsoil conditions.

Keywords Waste tyre bales · Embankment · Stability analysis · Settlement · Soft ground

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1 Introduction

Waste tyres are among the largest and most problematic sources of waste today. The waste tyre landfills constitute a significant burden for the natural environment: they burn for years and the smoke includes toxic chemicals. Since 2000 in Europe, the EU Landfill Directive has forbidden the disposal of waste tyres in landfills. However, waste tyres belong to the most reused waste materials because tyre rubber is a very dependable material, strong, elastic, flexible, durable, waterproof, and easy to recycle. Therefore, the product recycling of waste tyres is the preferred solution to this waste problem. The waste tyre-derived products (TDP), including whole tyres, tyre bales, shreds, chips, and crumb rubber, have begun to be used in civil engineering applications, particularly in various geotechnical solutions. The majority of these applications has addressed tyre-derived aggregate (TDA), i.e. shreds, chips, and crumb rubber (Humphrey and Blumenthal 2010; Ahn et al. 2015; Meles et al. 2016a). An effective alternative is the baling of whole waste tyres to produce cuboidal, lightweight, permeable bales (Winter et al. 2006; Simm et al. 2008; Duda and Siwowski 2020). The baling is nowadays the best way for the product recycling of waste tyres. It enables the reuse of the whole tyres with the possible use of low-energy processing.

Waste tyre bales have considerable potential for use in road engineering applications due to their unique properties, such as three times lower unit (specific) weight than traditional soils, high frictional resistance, favourable damping properties, and good drainage properties. In particular, the use of tyre bales in the construction of a lightweight embankment on the soft ground has the potential to satisfy the demand for low-cost materials exhibiting such beneficial properties. Since the bales weigh less than conventional filling materials, they can serve as an embankment filling while reducing the dead weight and inducing less settlement of subsoils. Besides, the tyre bales are easily handled enabling the use of small equipment for placement. The elimination of conventional filling requirements for compaction and moisture control makes construction with tyre bales easy and relatively fast. Therefore, the cost of using tyre bales in road engineering applications is less than that of conventional filling materials.

Waste tyre bales were first used in civil engineering in the late 1990s in the USA (Sonti et al. 2000). Since then, several dozen projects have been implemented in road construction, mainly in the USA, Canada, and Great Britain. Road applications of waste tyre bales include, but are not limited to embankment construction, slope stabilization and repair (landslides), road foundations over soft ground, gravity retaining structures (gabion-type), and backfill material for retaining walls. The most spectacular example of the waste tyre bales' use in the embankment structure is the section of the A-421 motorway near Bedford in England (Hodgson et al. 2012). The A-421 improvement scheme required the construction of the new dual carriageway and a realigned side road over two former borrow pits that have been partially infilled with up to 20 m of soft clay. The side road was constructed using lightweight fill comprising waste tyre bales supplemented with lightweight expanded clay aggregate (LECA). Approximately 4500 tyre bales were utilised to construct the embankment, equating to about 500,000 waste tyres. Waste tyre bales were also used as a lightweight fill in an embankment for Tampere Western Ring Road, Finland (Harri 2005). The subsoil consisted of a 10-m-deep weak clay layer. The bottom layer of the road embankment consisted of one layer of tyre bales surrounded by filter cloth and covered by a steel wire net. The tyre bale section of the embankment was about 130 m in length. Other road engineering applications of waste tyre bales are presented and discussed in the authors' review (Duda and Siwowski 2021).

Despite the successful applications of tyre bales in road embankment construction, the lack of design standards and the fear of soil and water contamination from the bales have historically limited the number of road engineering projects that used waste tyre bales. The latter problem seems to be gradually solved since a lot of research has been recently carried out in the field (Hennebert et al. 2014; Liu et al. 2020; Mohajerani et al. 2020; Duda et al. 2020). However, the user-friendly design methods to be used for tyre-baled structure evaluation are still waiting for elaboration. Up to date, the finite element method (FEM) was commonly used to model and evaluate the structural behaviour of geotechnical objects comprising TDA in various applications (Bosscher et al. 1997; Lopera Perez et al. 2016; Meles et al. 2016b; Kowalska and Chmielewski 2017; Mahgoub and El Naggar 2020). The comprehensive material testing of TDA was commonly required to determine the properties to be assumed in FE analysis. No such analysis or computational methods have been found by the authors regarding tyre bales. Although various tyre bale test results (Zornberg et al. 2005; Zornberg and LaRocque 2006; Freilich and Zornberg 2009) and construction specifications (Winter et al. 2006; Simm et al. 2008; PAS 108 2007) already exist, the lack of reliable design methods significantly limits the wider application of this sustainable material in road engineering. In particular, the lightweight embankments, which contain tyre bales as filling material, have to be carefully designed to check their stability and settlement, always critical in road construction.

The paper proposes the design approach for stability and settlement analysing for tyre-baled lightweight embankment founded on soft ground. The comparative study has been presented between the common medium sand-filled embankment and two tyre-baled structures with various granular interlayers: medium sand and rubber aggregate. The latter was proposed to enhance the sustainability of the lightweight embankment increasing waste tyre rubber utilization. Since the main benefit of using waste tyre bales in the embankment body is the substrate unloading, two soft subsoils have been considered in the study: sandy clay and silty clay, to check the efficiency of tyre bale application in both ground conditions. The common embankment analysis, which included stability, settlement, and subsoil bearing capacity checking, has been performed for three embankment cases and two subsoil conditions. However, to obtain the set of reliable material parameters to be applied in analysis, the comprehensive testing of filling materials, tyre bales, and "geocomposites", i.e. tyre bales with granulated interlayers, was carried out. In particular, the compressibility test and the direct shear tests delivered required design parameters. To facilitate further analysis, the equivalent material parameters for both geocomposites were calculated based on testing results and embankment geometry. This approach has been already validated against experiment in previous authors' work (Duda and Siwowski 2020) and seems to be adequate also in this study. The stability analysis for all cases has been performed using the simplified Bishop's limit equilibrium method and the finite element method. The latter method has been used to check settlement and subsoil bearing capacity, as well.

2 Problem Statement

To limit the subsoil settlement or the need for the expensive soil reinforcement in case of the soft ground under the embankment, the reduction of the embankment dead weight by introducing waste tyre bales into the structure has been proposed in this study. Figure 1 shows the embankment geometry assumed in the analysis. The embankment has a crest width of 9.5 m (7.0 m carriageway and 2 × 1.25 m shoulders), a height of 5.0 m, and a base width of 29.5 m, assuming the typical embankment slope of 1:2. Two cases have been considered in this study: case A is an embankment made of typical filing material, i.e. medium sand, while case B assumed the reduction of the embankment body dead weight by introducing waste tyre bales. The tyre-baled block located inside the embankment structure has a height of 2.7 m and an average width of 10.55 m. In addition to tyre bales, at least three horizontal interlayers were adopted in-between the tyre bales to reduce the settlement process due to bale compressibility, to enhance the interface strength, and, consequently, to gain the required stability and resistance of the whole structure. In the case of B, the total volume of the tyre-baled block (with interlayers) consists of about 55% of the embankment volume, with the minimum 0.6-m-thick medium sand layers laid on both slopes. It means the dead load caused by an embankment body on the soft ground could be decreased considerably by more than 30%. However, to ensure this solution could be applied in road embankment construction, the embankment stability and settlement have to be checked assuming the actual material parameters, estimated in the appropriate tests, and using the appropriate analytical or numerical methods.

The actual material parameters of tyre bales and accompanying filling materials were estimated experimentally. The full-scale compressibility test and direct shear test were carried out to evaluate Young's modulus and Poison's ratio of a tyre bale (in the first test), and to determine the interface strength between tyre bales and filling materials (in the latter). Two filling materials as interlayers were considered in this study: medium sand (as for the whole embankment body in case A) and waste tyre shreds (rubber aggregate). The latter was used to enhance the sustainability of the proposed solution.

As far as a subsoil is considered, two options of a soft ground were assumed in the analysis: sandy clay and silty clay, both in drained conditions and soft-plastic state. These ground types most often occur as a road substrate in the southeast region of Poland for which this study has been undertaken. Although the undrained condition often controls the stability, the drained soil conditions were assumed in the analysis to obtain the comparison results independent of a particular location (i.e. groundwater table, saturated soil parameters). Moreover, since no particular location was chosen for comparison, no undrained shear strength could be determined in laboratory tests. Finally, the initial pre-consolidation is the most popular way to improve substrate condition in the case of both soft subsoils; after pre-consolidation, the drained conditions will control the embankment stability; that is why no compressibility and time-dependent settlement from the consolidation of the substrate were evaluated. Furthermore, since this is a comparative study to assess the efficiency of waste tyre bales as embankment filling, the homogeneous substrate was assumed in calculation and subsoil parameters were slightly adjusted to check the rotational stability of a whole embankment, not only local slope stability. Particularly, the parameters of the softer

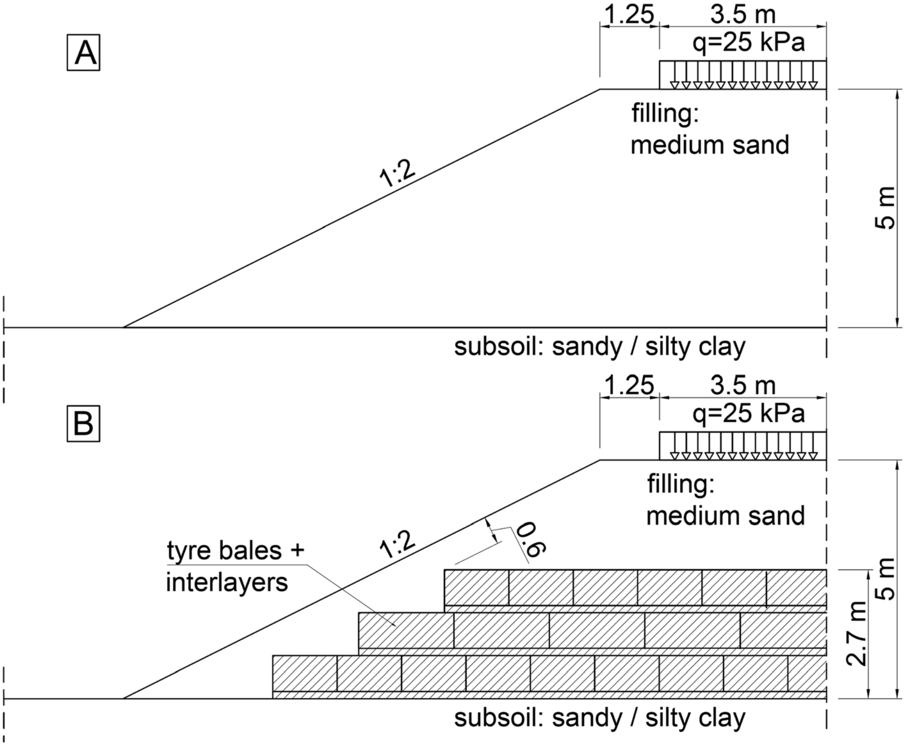

Fig. 1 Embankment geometry and composition assumed in the study: (a) embankment filled with medium sand only; (b) embankment filled with a block made of tyre bales and interlayers

subsoil (silty clay) were adjusted to obtain a safety factor $Fs \approx 1.0$, which assures the stability of the embankment slope to be under control. The basic material parameters of both subsoils chosen in this study are given in Table 1.

The embankment stability and settlement analysis have been performed to check the feasibility of the proposed solution and to compare it with the behaviour of a typical embankment made of common medium sand. The quantitative comparison has been carried out using analytical and numerical calculations of each embankment case under the traffic load assumed as q = 25 kPa according to the Polish Regulation (Regulation 2.03.1999 1999). The following limit states have been used to compare all designs: embankment stability, settlement, and bearing capacity of subsoil. For all computing

Table 1 Basic parameters of subsoils assumed in the study

Subsoil	Unit weight (kN/m^3)	Young's modulus (MPa)	Poisson's ratio (-)	Cohesion (kPa)	Friction angle (°)	Bearing resistance* (kPa)
Sandy clay	20.0	15.0	0.3	10.0	12.0	233.0
Silty clay	18.0	10.0	0.3	10.0	7.0	109.4

*Characteristic value according to Annex D of (PN-EN 1997-1 2008), a sample analytical method for bearing resistance calculation in drained conditions the characteristic values of material parameters (waste tyres, granular filling, subsoil) and applied loads have been taken into account, no partial safety factors have been included in this comparative analysis. Such kind of direct comparison enabled us to assess easily the effectiveness of using waste tyre bales as filling material for road embankments constructed on soft ground.

3 Materials

3.1 Waste Tyre Bales

Tyre bales considered in this study comprised whole waste passenger-vehicle tyres of R14–R17 type (diameter) compressed into a lightweight block. The production of tyre bales was performed according to British specification (PAS 108 2007). A typical tyre bale used in this study is shown in Fig. 2. The average numerical values for bale's dimensions were determined using six bales by taking five measurements of the length (L), width (B), and height (H) of each bale and calculating the average of each dimension (Fig. 2b). The average dimensions, volume, weight, and the unit (volumetric) weight calculated using the average volume are provided in Table 2.

3.2 Filling Materials

Two filling materials have been considered in this study to supplement tyre-baled filling block: medium sand and rubber aggregate (i.e. waste tyre shreds), with 0.25–1.00-mm and 4.0–20.0-mm granulation, respectively. The basic filling material characteristics were determined according to (PN-B-04481 1988), while the direct shear test was conducted with the AB-2a direct shear apparatus according to (PKN-CEN ISO/TS 17892-10 2009). The basic material characteristics determined in these tests are provided in Table 3.

The shear strength envelopes for rubber aggregate are somewhat nonlinear and the friction angle is greater at lower confining pressures. A bilinear strength envelope was defined by Humphrey and Manion (Humphrey and Manion 1992) and Bernal et al. (Bernal et al. 1996). In own laboratory tests, the mechanical parameters of rubber aggregate were determined for normal stresses above 70 kPa. Typically, in the low normal stress range, the friction angle of the rubber aggregate oscillates at about 35°.

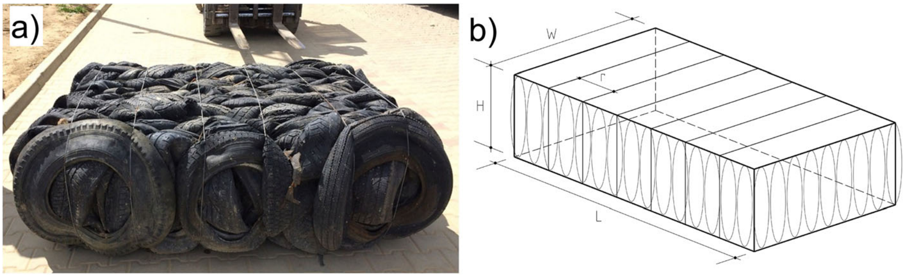

Fig. 2 Typical waste tyre bale used in this study: (a) general view; (b) scheme of basic dimensions

Table 2 Basic dimensions and weights of a waste tyre bale

Number of tyres in a bale	Length L (m)	Width B	Height H	Area A (m^2)	Volume V (m^3)	Weight G (kN)	Unit weight γ_{bale} (kN/m^3)
135	2.055	1.312	0.747	2.697	2.014	10.11	5.02

4 Methods

4.1 Determination of Basic Parameters

4.1.1 Compressibility Test

The Young's modulus (E_v) and the Poison's ratio (ν) for a tyre bale are the basic design parameters of high importance, required for further analysis. Therefore, the evaluation of both parameters has been carried out based on compressibility test results. The non-linear deformation of the tyre bale can be represented by either an average linear modulus over the stress range of interest or a series of secant moduli with the applied load. The first approach was applied by the authors to assess the approximate Young's modulus value.

The Young's modulus for each stress range considered was assessed according to the following formula:

$$E_v = \frac{\sigma_v}{\Delta\varepsilon_v} \tag{1}$$

where:

- σ_v – maximum stress in the considered load range;
- $\Delta\varepsilon_v$ – vertical strain increase in the considered load range.

Table 3 Basic material characteristics of filling materials

Filling material	Unit weight (kN/m^3)	Young's Modulus (MPa)	Poisson's ratio (-)	Cohesion (kPa)	Friction angle (°)	State
Medium sand	18.5	80.0	0.25	0.1	35.2	Medium compacted
Rubber aggregate	4.61	0.5	0.25	11.7–20.0* 10.5	15.6–39.2* 20.5	Loose

*Acc. to (Humphrey and Manion 1992; Bernal et al. 1996)

The relevant values of stresses and strains were calculated as follows:

$$\sigma_v = \frac{P_{max}}{A} \tag{2}$$

and

$$\varepsilon_v = \frac{v_{avg}}{H} \tag{3}$$

where:

- P_{max} — failure load in compression test;
- v_{avg} — average vertical displacement at failure load;
- A and H — area and height of the bale (Table 1).

The Poisson's ratio was defined as the horizontal strain divided by the total vertical strain of the tyre bale's material. The equation for the Poisson's ratio determination is as follows:

$$\nu = \frac{\varepsilon_h}{\varepsilon_v} \tag{4}$$

where:

- ε_h — maximum horizontal strain in the considered load range;
- ε_v — vertical strain in the considered load range.

The maximum horizontal strain ε_h was calculated on the assumption of bale symmetry as the double horizontal deformation $2h_{avg}$ obtained at P_{max}, divided by the average bale length L (Table 1):

$$\varepsilon_h = \frac{2\Delta h}{L} \tag{5}$$

It should be noted that horizontal strain was calculated only for the bale's deformation in the length direction (*L*), because the perpendicular deformation (*B*-direction) was restrained by the wire ties (Fig. 2a).

A series of compression tests were conducted to evaluate the behaviour of tyre bales when subjected to vertical normal loads and to determine Young's modulus and Poisson's ratio for tyre bales. Compression tests on the tyre bales were conducted following the standard (ASTM D2166-00 2000). Six full-size tyre bales were used in the compression test. The top and bottom loading platens consisted of three concrete slabs (two bottom and one top) with dimensions 0.15 × 1.50 × 3.00 m that extended in all directions beyond the edge of the fully loaded specimen (Fig. 3).

The load versus vertical and horizontal deformation plots was obtained to characterise the bale behaviour under compression. In Fig. 4, the typical behaviour of the

Fig. 3 Compression test stand

exemplary bale is presented for vertical and horizontal deformations, respectively (the load cycle up to P=250 kN).

The approximate Young's modulus for the tyre bale was in the range of 713.5 to 904.0 kPa at a medium stress level of about 90 kPa (P=250 kN). The average Young's modulus value equals 826 kPa and is close to the values reported in (Zornberg et al. 2005; Freilich and Zornberg 2009) for a similar test setup. The horizontal deformation measurements indicated a relatively low Poison's ratio on the order of 0.11 at the medium stress level of about 90 kPa (P=250 kN). However, lateral movement at low and medium stress levels is likely restricted by the combination of compression during baling and vertical orientation of the tyres in the bale. Values reported in (Zornberg et al. 2005) range from 0.1 to 0.2 for stresses less than 47.9 kPa, and increase up to 0.3–0.4 at higher stresses, while the ones reported in (Freilich and Zornberg 2009) range from 0.08 to 0.24 at maximum stress of 31.1 kPa. The comparison with (Zornberg et al. 2005; Freilich and Zornberg 2009) may validate the results obtained in this study.

4.1.2 Direct Shear Tests

A full-scale direct shear testing procedure was carried out to determine the interface strength between tyre bales and filling material. This test is similar to that of a soil direct shear test according to (PKN-CEN ISO/TS 17892-10 2009), in which the material is

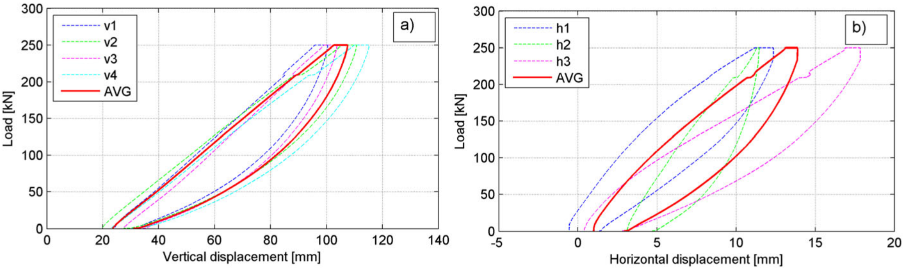

Fig. 4 The behaviour of tyre bale under the load P=250 kN: (a) vertical displacements (four LVDTs located in four corners of the top platen); (b) horizontal displacements (three LVDTs located on one tyre bale's side)

forced to fail horizontally along a defined shear plane. The test procedure involved stacking two bales and applying a normal and horizontal (shear) load to the top (sliding) bale while holding the bottom one stationary. A filling material interlayer was placed and compacted on top of the stationary bale to represent the tyre bale–filling material interface and to determine the interface strength. The thickness of the interlayer was chosen as about 150 mm to simulate common tyre bale composition in an embankment body (Hodgson et al. 2012; Harri 2005) and to ensure that failure occurred along the interface and not within the filling material. The sliding bale was placed on the interlayer and displaced horizontally with a hydraulic actuator, which was statically mounted on a reaction column. Three sliding tyre bales were applied in the direct shear test, while the bottom bale was held stationary in the self-supporting wooden box filled with the respective material (Fig. 5).

The normal load was applied gradually by placing additional weight on the sliding bale. The horizontal load was applied with a speed of 4 mm/min until slippage occurs, i.e. the substantial horizontal displacement of sliding bale was observed with a noticeable decrease of the horizontal load or the horizontal displacement exceeded 8–10% of the bale length. After a slippage had been observed, the horizontal loading was stopped and the actuator piston’s displacement was maintained for about 5 min until the load stabilised. This stabilised value of the horizontal load was further considered as the failure shear load. Each tyre bale was tested three times. Eight LVDT transducers were placed at the front, rear, and sides of the sliding bale to measure the horizontal and vertical displacements.

The horizontal load versus time and displacement curves were plotted to evaluate the development of shear resistance along the tyre bale–filling interface as well as to determine the failure load along the interface (Fig. 6). The subsequent phases (I, II,

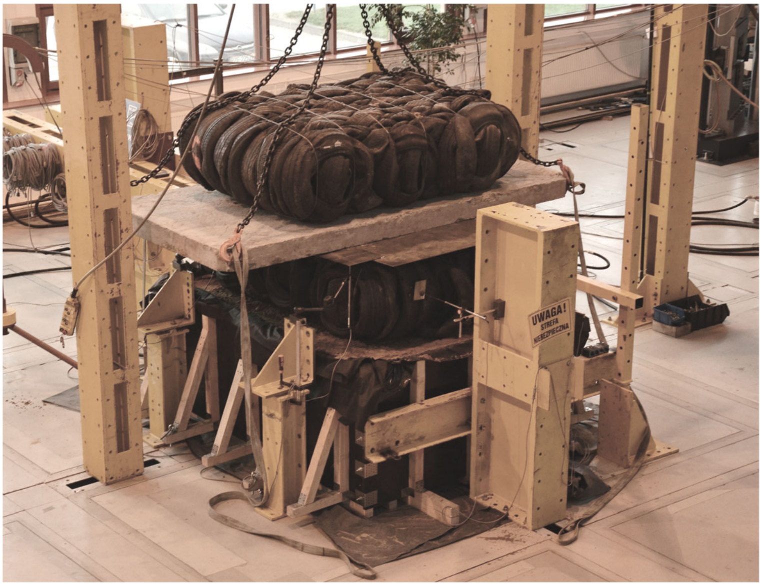

Fig. 5 Direct shear test stand

and III) of the specimen's behaviour under load are marked with colour and the failure load was given as well (see respective arrows).

The shear (τ) and normal (σ) stress along the tyre bale interface was defined as the applied load divided by the average area of the tyre bale. The failure loads were used to define the shear strength envelope, which corresponded to the failure points of 12 tests conducted for each filling material. A linear trend line was used to represent a failure envelope passing through the points. The shear strength envelopes are shown in Fig. 7 as a function of the applied normal stress. To derive the shear strength of a tyre bale–filling material interface, the Coulomb–Mohr (C-M) failure criterion was used (6):

$$\tau = \sigma \cdot tg\varphi + c \tag{6}$$

where:

- τ — shear strength;
- σ — normal stress;
- φ — friction angle of the material (in this case: friction at a tyre bale–filling interface);
- c — cohesion of the material (in this case: cohesion at a tyre bale–filling interface).

The interface shear strength parameters determined from linear regression of the test results are provided in Table 4. The coefficients of determination R^2 for both envelopes are acceptable, confirming that observed test results are very well replicated by the models τ (σ), based on the proportion of total variation of results explained by the envelope. However, for the tyre bale–filling material interface, the friction angle is about 16% and 23.5% lower for medium sand and rubber aggregate, respectively, as compared with the common angle of φ=35°. It showed that the frictional response along the tyre bale interface cannot be directly predicted by the direct shear testing of the filling material.

4.1.3 Material Parameters for Calculations

To characterise correctly the materials and to attain acceptable results in analytical and numerical calculations, reliable material data must be adopted. The subsoils, as well as medium sand and rubber aggregate for tyre-baled block interlayers, are represented by

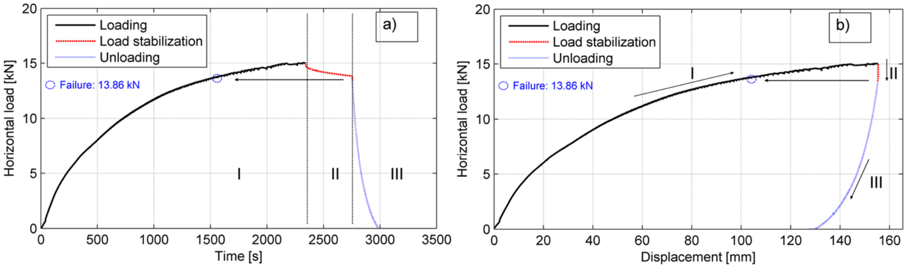

Fig. 6 Exemplary curves for tyre bale–medium sand shear test: (a) load–time curve; (b) load–displacement curve

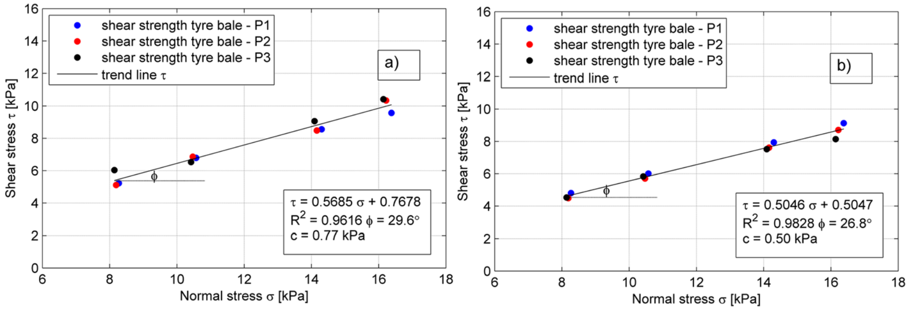

Fig. 7 Shear strength envelopes: (a) tyre bale–medium sand interface; (b) tyre bale–rubber aggregate interface

the standard linear elastic–perfectly plastic C-M models, which involve at least four basic parameters, i.e. Young's modulus E, Poisson's ratio ν, cohesion c, and friction angle φ. The material parameters for the two subsoils are chosen according to relevant standards (see Table 1), while the C-M model parameters for filling materials of both interlayers were determined using direct shear tests and are provided in Table 3.

The rubber tyre bales were modelled as a perfectly elastic material according to Hooke's law because there was no evidence of plastic damage encountered during the laboratory tests. The Young's modulus E and Poisson's ratio ν determined in the compressibility test were taken for the calculation. However, to simplify the analysis and to facilitate a numerical embankment model, the tyre bales and the interlayers were modelled jointly as a "geocomposite" material, with the equivalent material parameters concerning the actual height/depth of two components: 0.75 m for tyre bales and 0.15 m for the interlayer, calculated according to formulas (7) to (9):

$$\gamma_{eqv} = \frac{\sum \gamma_i \times t_i}{\sum t_i} \tag{7}$$

$$E_{eqv} = \frac{\sum E_i \times t_i}{\sum t_i} \tag{8}$$

$$v_{eqv} = \frac{\sum v_i \times t_i}{\sum t_i} \tag{9}$$

Table 4 Shear strength parameters of tyre bale–filling interface

Interlayer filling material	Cohesion c (kPa)	Friction angle φ (°)	Determination coefficient R^2
Medium sand	0.77	29.6	0.962
Rubber aggregate	0.50	26.8	0.983

where:

γ_{eqv}, E_{eqv}, ν_{eqv} — equivalent material parameters of "geocomposites";
γ_i, E_i, ν_i — material parameters of the particular layer (tyre bale or granular interlayer) according to relevant test results;
t_i — actual height/depth of the relevant layer.

The equivalent material parameters of both "geocomposites" are given in Table 5, while the final set of material data applied in the calculation is provided in Table 6.

4.2 Methods of Analysis

In the design of road embankments, the quantitative determination of the stability of slopes is always necessary. The embankment slope stability is typically controlled by the ratio between the shear strength of the embankment's material and the shear stress induced by the acting load, both quantities integrated over a potential sliding surface. This ratio can be expressed in terms of a safety factor (*Fs*). A slope can be globally stable if the safety factor, computed along any potential sliding surface running from the top of the slope to its toe, is always larger than 1.0. The smallest value of the safety factor will be taken as representing the global stability condition of the slope. Similarly, a slope can be locally stable if a safety factor larger than 1.0 is computed along any potential sliding surface running through a limited portion of the slope (for instance only within its toe). Theoretically, an *Fs* value greater than 1.0 indicates a stable slope while an *Fs* value equal to 1.0 implies that the slope is in equilibrium. However, values of the global or local safety factors close to 1.0 indicate marginally stable slopes that require monitoring and/or slope stabilization to increase the safety factor and reduce the probability of a slope movement.

Several methods can be used to compute the safety factor of a slope. One of them is the simplified Bishop's limit equilibrium method of slices (Bishop 1955). This method has been chosen in this study because it can provide a simple and quick evaluation of a potential slope instability as well as it can be used for the reliable comparison of various embankment construction techniques (Hungr 1988; Lee et al. 1995; Ji et al. 2020).

However, nowadays the majority of engineers and researchers perform the embankment design using the finite element method (FEM) because Bishop's limit equilibrium slicing method is known as an uncertain static problem, solved by assuming a distribution of internal forces. As such, different assumptions can result in varied results. Due to this inherent engineering practical weakness, FEM is now a choice. Some

Table 5 Equivalent material parameters of "geocomposites" made of tyre bales and interlayer's material

Parameter	Unit	Tyre bale	Interlayer		Geocomposite	
			Mid. sand	Rubber agg.	Tyre and sand	Tyre and rubber
Unit weight (density) γ	(kN/m^3)	5.022	18.5	4.61	7.27	4.95
Young's modulus E	(MPa)	0.826	80.0	0.5	14.02	0.77
Poisson's ratio ν	(--)	0.11	0.25	0.25	0.13	0.13

Table 6 Linear elastic properties of embankment and subsoil materials applied in calculations

Embankment fill/subsoil material	Unit weight (kN/m^3)	Young's modulus (MPa)	Poisson's ratio (-)	Cohesion (kPa)	Friction angle (°)
Medium sand	18.5	80.0	0.3	0.1	35.2
Tyre bales and sand interlayers	7.27	14.02	0.13	0.77	29.6
Tyre bales and rubber interlayers	4.95	0.77	0.13	0.50	26.8
Sandy clay (subsoil 1)	20.0	15.0	0.3	10.0	12.0
Silty clay (subsoil 2)	18.0	10.0	0.3	10.0	7.0

researchers have compared the results between the limit equilibrium method and FEM (Liu et al. 2015), concluding that FEM provides the best and most accurate Fs result, as it is better able to explain the behaviour of soil stress and eliminate stress assumptions used in the limit equilibrium method. The safety factor analysis is based on the assumption that the total load applied to the soil body is introduced in a single load step. The actual Fs is most commonly evaluated using the strength reduction method, i.e. reduction of strength parameters c and φ (Luo et al. 2016). This method has been used for the first time by Zienkiewicz et al. (Zienkiewicz et al. 1975) to calculate slope safety factors based on the C-M model. The strength reduction method does not require assumptions on the form or location of the failure surface, because failures occur naturally through the zone in the soil mass where soil shear strength is unable to resist the applied shear stress (Griffiths and Lane 1999). This means that the critical slip surface is automatically obtained from the increased shear stress when the shear strength decreases.

Using the strength reduction method in the FEM environment, the safety factor Fs is defined as a scalar multiplier that reduces the original shear strength parameters c and φ to obtain the state of failure. Searching for the critical value of the safety factor Fs requires a systematic modification (reduction) of strength parameters c and φ leading to failure. In the framework of the Newton Raphson method, the state of failure is determined as the state for which the solution fails to converge.

FEM analysis requires the establishment of data in geometric modelling, material constitutive relationships, finite element mesh, and boundary and loading conditions. Geometric data, namely height, crest width, and gradient of side slopes are among the important parameters in the embankment design. The values as shown in Fig. 1 were adopted in this analysis to simulate the assumed embankment structure (cases A and B) and to obtain the safety factors for both cases and two various soft ground substrates.

Based on the own material testing described above, the properties of different filling and subsoil sets were created and assigned to respective material models. Linear elastic properties of the embankment and subsoil materials were adopted to be applied in material models (Table 6). The elastic–perfectly plastic constitutive C-M model was employed to simulate the plastic behaviour of fills and soils in this study. Circular slip surfaces were assumed for models. After the geometrical model was created and material models were assigned, finite element mesh was automatically generated using different mesh settings. Most of the earlier slope stability analyses were conducted using 2-D FE methods and have been proven to be effective (Griffiths and Lane 1999; Fredlund et al. 2017). Hence, 2-D FE analysis was employed in this study to conduct the slope stability analysis because 3-D FE analysis is too time consuming.

The filling, tyre-baled block, and subsoils were modelled using triangular and quadrangular elements with a side size of 0.6 m. The total number of elements was 4512, of which 2569 plate, 479 beam, and 1437 contact elements. The total number of nodes was 3698. No particular contact between the tyre-baled block and medium sand filling was modelled; however, a commonly used “hard normal contact” was assumed in the model, and the C-M model’s material properties were specified for the block-soil contact. Well-known commercial geotechnical software GEO5 was used in both Bishop’s limit equilibrium method and FEM analysis (Geotechnical Software Suite GEO5 – user’s guide manual 2019). The embankment and subsoil were modelled taking into account the working area of 54.5 × 20 m in Bishop’s method and FEM analysis (Fig. 8).

5 Results and Discussion

5.1 Stability

To evaluate the stability of embankments with various filling, the Polish recommendations based on European research were used (Wysokiński 2011). The slippage likelihood is assessed there by the stability safety factor F_s as follows: $F_s > 1.5$ — very unlikely; $1.3 < F_s < 1.5$ — unlikely; $1.0 < F_s < 1.3$ — very likely. The stability safety factor F_s is calculated using characteristic soil parameters as well as characteristic load (i.e. without any partial safety factors).

As far as the Bishop’s method is concerned, in the case of sandy clay, the slippage is very unlikely for all embankment cases (Fig. 9 left). Regardless of interlayer material, the tyre-baled filling does not reduce the embankment stability; moreover, in the case of the medium sand interlayer, tyre-baled filling enhances the embankment stability as compared to the medium sand embankment. In silty clay conditions, the softer subsoil generally worsens the stability of about 10–20% (Fig. 9 right). However, also in this case, the application of tyre bales enhances the embankment stability and changes the slippage likelihood from “very likely” to “unlikely”. Furthermore, in both soft soil conditions, unless common sand embankment, in case of tyre-baled structure, the slip surface is located mostly within embankment slope, showing good rotational stability independent on subsoil conditions.

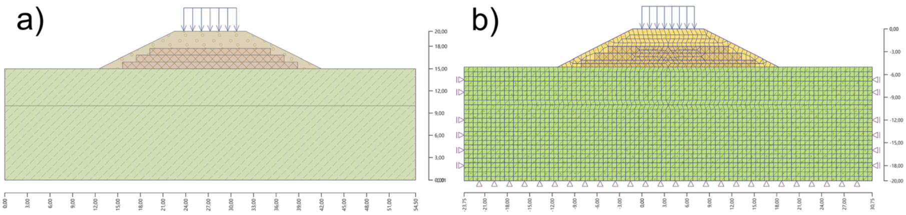

Fig. 8 Working areas in stability analysis: (a) Bishop’s method; (b) FEM

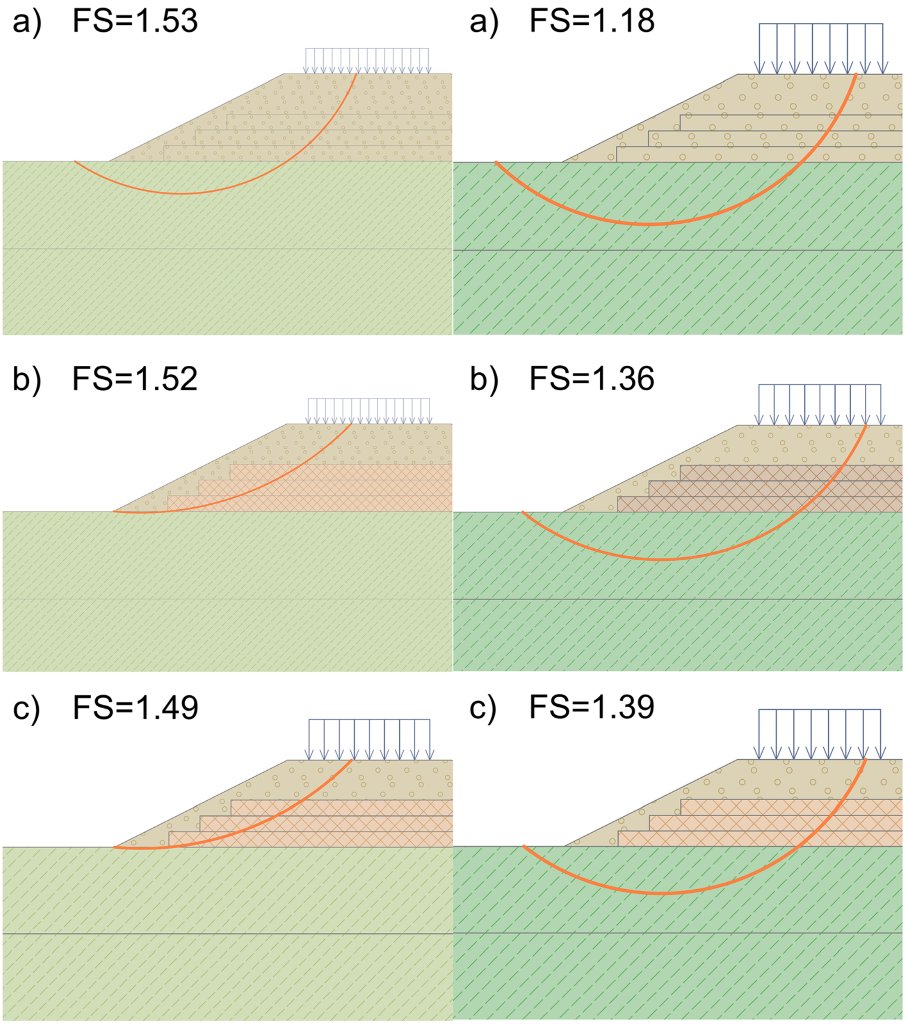

Fig. 9 Results of stability analysis according to Bishop's method in sandy clay (left) and silty clay (right) conditions for: (a) common embankment built of medium sand; (b) embankment filled with tyre bales and medium sand interlayers; (c) embankment filled with tyre bales and rubber interlayers

The corresponding results of FE analysis are provided as the *Fs* values and the equivalent plastic deformation maps (Fig. 10). The C-M failure criterion was employed for the evaluation of fillings and subsoils. The maps show embankment and substrate areas, in which the plasticity occurred (i.e. the C-M failure criterion was exceeded, in (%)) and the deformed shape of the slope shows the failure mechanism. As far as F_s value is considered, the FEM results are generally lower in the range of 5–15% as compared to the corresponding Bishop's values. It is due to local instability at slope toe as well as the numerical internal instability of "geocomposites" made of tyre bales and respective interlayers. However, the slope toes are commonly strengthened in soft subsoil conditions and the tyre-baled "geocomposites" cannot become unstable in reality. Therefore, in the case of embankment filled with tyre bales, the safety factors evaluated using Bishop’s method seem to be more reliable.

In contrary to Bishop’s method, in the case of sandy clay, the safety factor F_s of the tyre-baled embankment decreases slightly in the range of 2–8%, the highest percentage for rubber interlayers (Fig. 10 left). However, in all three embankment cases, the

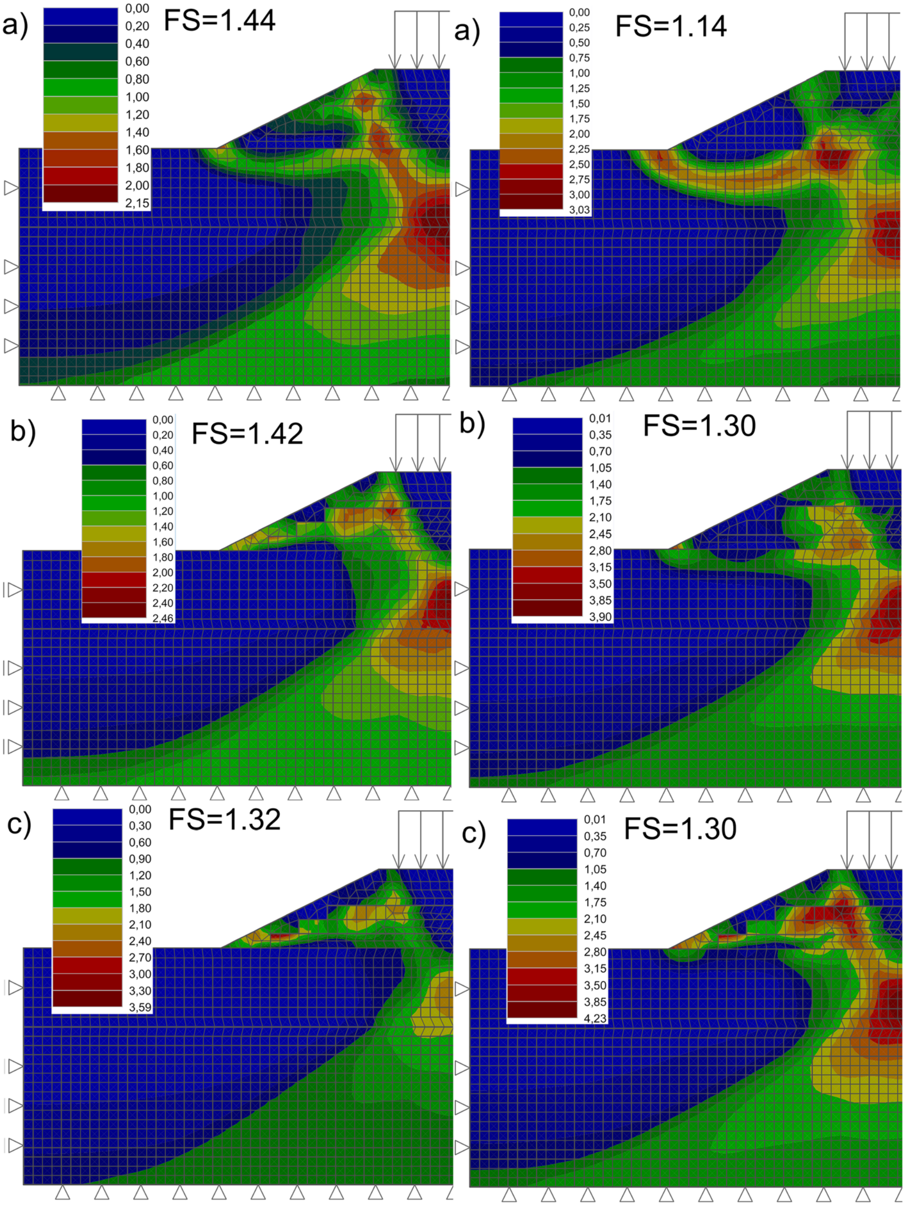

Fig. 10 Results of stability analysis according to FEM in sandy clay (left) and silty clay (right) conditions for: (a) common embankment built of medium sand; (b) embankment filled with tyre bales and medium sand interlayers; (c) embankment filled with tyre bales and rubber interlayers

slippage likelihood is “unlikely”, confirming the safety of embankment with tyre-baled filling. In the case of silty clay, the application of tyre bales considerably increases the embankment stability (13%, regardless of interlayer type) and changes the slippage likelihood from “very likely” to “unlikely” (Fig. 10 right). In the latter subsoil case, the effectiveness of tyre bales is slightly better as compared to sandy clay subsoil.

The equivalent plastic deformation maps enable evaluating of plastic deformation in the embankment’s substrate. For the lightest embankment with tyre-baled block and rubber interlayers, no plastic deformation of the substrate is observed regardless of subsoil. The change of interlayers’ material into medium sand increases slightly plastic substrate deformation, however, in the case of silty clay only. No rotational slip surface is observed for tyre-baled embankments, and only little local (internal) instabilities can be seen on the respective deformation maps. On contrary, for common medium sand embankment, the typical circular slip surface is revealed (as in Bishop’s method) and located within embankment slope and substrate.

Finally, it should be noted, that the strength parameters of the tyre-baled filling, assumed in FE analysis, were determined in the direct shear tests of the tyre bale–interlayer interface (Table 4). Such assumption is rather conservative because tyre bales are self-stable large size blocks and their placing inside embankment prevents the formation of the circular or cylindrical slip surface. Hence, the stability safety factor F_s obtained in FE analysis seems to be underestimated and the real values are much closer to those determined by Bishop’s slice method. On the other side, the comparison between two calculation methods reveals that the FE material model of the tyre-baled embankment as assumed in this study can be employed to evaluate the stability of tyre-baled soil structure with sufficient reliability.

5.2 Settlement

FE analysis enabled evaluating the embankment’s settlement depending on the filling material (i.e. with or without tyre bales) and substrate type (sandy clay or silty clay). The deadweight of the embankment body, as well as the assumed traffic load, was considered in the comparative analysis. A significant settlement reduction has been expected due to the decrease of the dead weight of embankment constructed with the tyre bales. The FEM settlement results were also compared to an allowable value according to the Polish requirements (Regulation 2.03.1999 1999), i.e. 100 mm.

The subsoil settlements in the centre axis of the embankment are provided in Table 7 along with the respective settlement reduction due to the application of the tyre-baled filling. The reduction in the range of about 28–33% is revealed; the higher value was obtained for rubber interlayers between tyre bales and silty clay subsoil. However, for silty clay, no one solution meets the allowable settlement requirement (i.e. 100 mm); therefore, the subsoil improvement has to be implemented before embankment construction. However, in the case of the tyre-baled filling, the substrate area which requires improvement is much smaller. In the slightly better subsoil conditions (i.e. sandy clay), although the common medium sand embankment requires subsoil improvement, the application of the tyre-baled blocks (regardless of the interlayer type) effectively reduces the settlement below the allowable threshold; thus, no intervention to the substrate is required.

Table 7 Subsoil displacements and normal stresses in the centre axis of embankment determined in FE analysis

Subsoil	Parameter	Filling of embankment			Reduction (%)	
		Medium sand	Tyre bales and sand interlayers	Tyre bales and rubber interlayers	Tyre bales and sand interlayers	Tyre bales and rubber interlayers
Sandy clay	Displacement z (mm)	123.7	89.1	89.4	28.0	27.7
	Normal stress σ (kPa)	90.14	70.30	72.27	22.01	19.82
Silty clay	Displacement z (mm)	231.7	154.5	155.2	33.3	33.0
	Normal stress σ (kPa)	93.77	69.33	70.42	26.06	24.9

The detailed analysis of vertical displacements (Fig. 11) reveals that apart from the substrate settlement (see Table 7), the internal settlement of the embankment body also occurs due to filling consolidation. For the common medium sand embankment and the tyre-baled embankment with sand interlayers, the internal settlements of 8.1 mm and 21.5 mm, respectively, are negligible. Such small settlement values can be levelled during embankment construction. However, in the case of the tyre-baled embankment

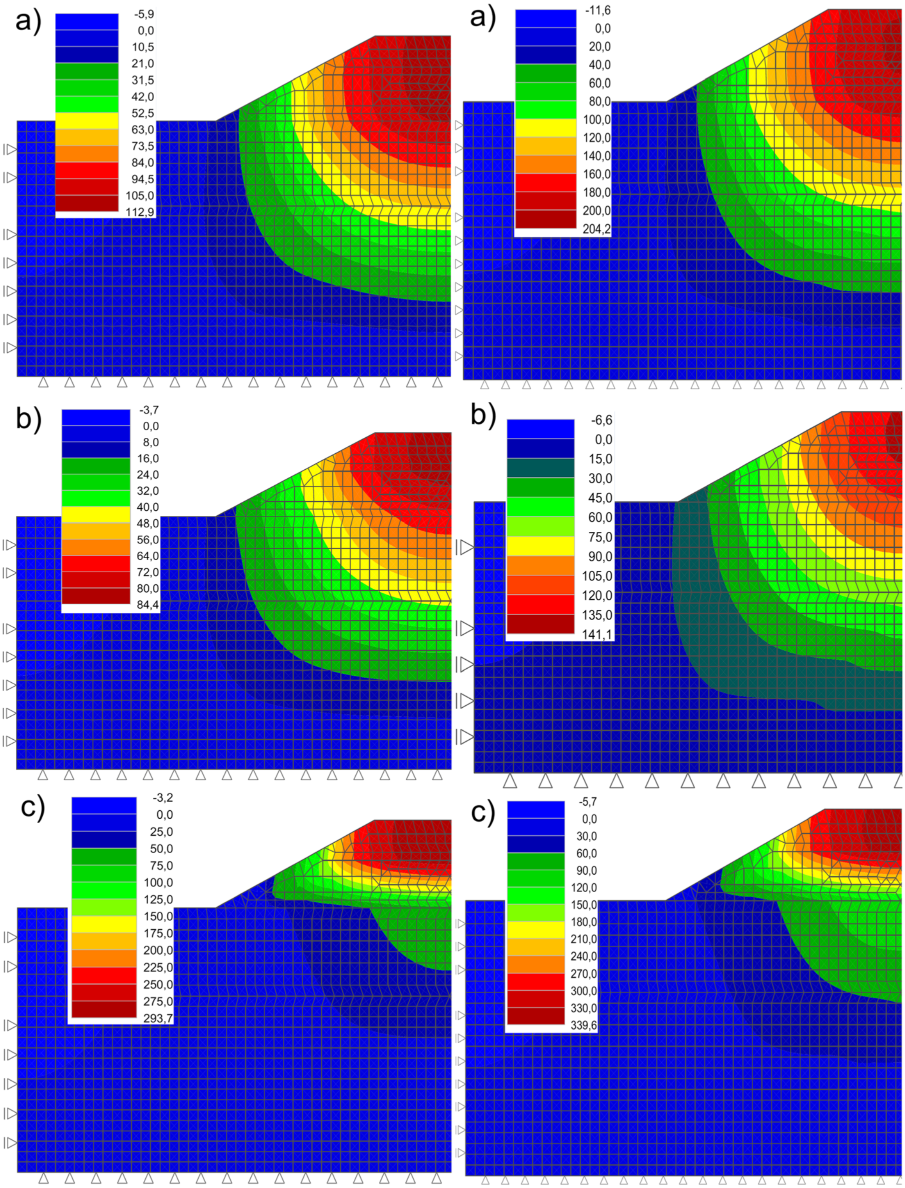

Fig. 11 Vertical displacements of sandy clay (left) and silty clay (right) subsoils for: (a) common embankment built of medium sand; (b) embankment filled with tyre bales and medium sand interlayers; (c) embankment filled with tyre bales and rubber interlayers

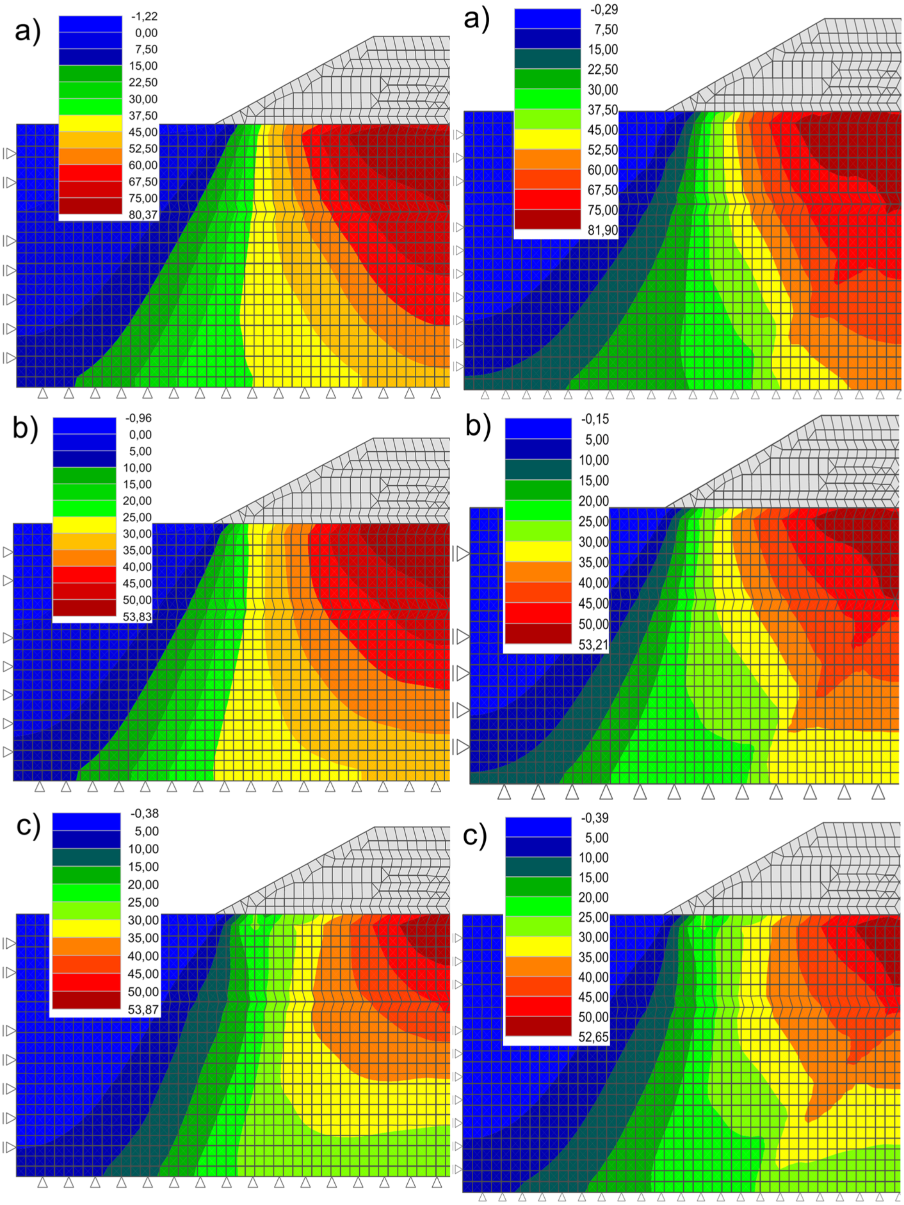

Fig. 12 Normal stresses in sandy clay (left) and silty clay (right) subsoils for: (a) common embankment built of medium sand; (b) embankment filled with tyre bales and medium sand interlayers; (c) embankment filled with tyre bales and rubber interlayers

with rubber interlayers, the internal consolidation settlement is 223.5 mm, which significantly increases the overall embankment's settlement well above the allowable threshold. It restricts the use of the third embankment solution to much better subsoil conditions as compared to soft subsoils assumed in this study.

5.3 Subsoil Bearing Capacity

Subsoil bearing capacity checking is one of the necessary steps in the design of the embankment. The numerically determined normal stresses in the centre embankment axis for both subsoil conditions are provided in Table 7. The respective stress reduction due to the application of the tyre-baled filling is also presented in the table. The stress reduction in the range of 20–26% is revealed; the higher value was obtained for sand interlayers between tyre bales and silty clay subsoil. However, for both subsoils, the normal stresses induced by the embankment body and traffic load are much smaller than the characteristic bearing capacity of respective soil (Table 1). Even in the case of the common medium sand embankment, the bearing capacity of the subsoil is exhausted only in 39% and 86% for sandy and silty clay, respectively. In the case of using tyre-baled filling, the exhaustion of subsoil bearing capacity can be further reduced in the range as shown in Table 7. In terms of the assumptions adopted in this study, the subsoil bearing capacity does not control the lightweight embankment design. Except for the slight decrease of the influence surface and depth as shown in normal stresses maps (Fig. 12), the application of tyre bales has no practical significance in the cases under consideration.

6 Conclusions

The stability and settlement analysis of a lightweight embankment filled with waste tyre bales and founded on the soft subsoil have been presented in the paper. Two lightweight embankments filled partially with the tyre-baled blocks consisting of the bales and granular interlayers have been compared with the common embankment constructed with medium sand only. Two soft subsoils have been taken into account in the aforementioned analysis to check their influence on the structural behaviour of a lightweight embankment. The simplified Bishop's limit equilibrium method of slices and the finite element method using the strength reduction approach have been applied in the analysis. The crucial input parameters for calculation in both methods (i.e. γ, E, ν, c, φ) have been determined experimentally for all embankment components. To simplify the analysis and to facilitate a numerical model, the equivalent "geocomposite" material for the tyre-baled filling has been defined based on material parameters for each component and special averaging procedure. This approach has been partially validated in previous authors' studies (Duda and Siwowski 2020). Using the "geocomposite" parameters, the comparative calculations have been performed, which resulted in the stability factors of safety F_s, the settlement values, and the stresses in the subsoil for each embankment case under consideration. The comparison of the resulting values has allowed assessing the effectiveness of using waste tyre bales as a filling of road embankment when founded on soft substrate.

Taking into account the results of the analysis, the following conclusions can be drawn in terms of waste tyre bale application efficiency in road embankments:

- generally, the application of tyre bales enhances the embankment stability; in the case of sandy clay, the slippage is "very unlikely" ($F_s > 1.5$) and in the case of silty clay, the tyre bales change the slippage likelihood from "very likely" to "unlikely";

in the tyre-baled embankments, the slip surface is located mostly within embankment slope, showing good rotational stability, independent on substrate conditions; the stability safety factors estimated using the FEM analysis are generally lower as compared to the Bishop's method in the range of 5–15%.

- in sandy clay subsoil condition, the application of the tyre-baled blocks (regardless of the interlayer type) effectively reduces the embankment settlement well below the allowable limit, although the common sand embankment requires subsoil improvement to meet this requirement; however, for silty clay, no one tyre-baled solution meets the requirement; moreover, in case of the tyre-baled embankment with rubber interlayers, the embankment body consolidation settlement is significant, thus excludes the use of this solution on soft grounds.
- the normal stress reduction in subsoil due to the application of the tyre-baled filling is in the range of about 20–26%; moreover, the bearing capacity of the subsoil is exhausted only in 39% and 86% for sandy and silty clay, respectively.

Despite the simplified numerical approach that has been used, the performed calculation has revealed that the use of a lightweight embankment filled with waste tyre bales could be an efficient solution when founded on soft substrate. However, the precision degree of the evaluation depends on the quality of determination of the material parameters but also the applied calculation approach. The information from this study can be used to widespread the use of tyre-balled embankments and to develop guidance system and numerical modelling for their design.

Code Availability (Software Application or Custom Code) Geotechnical Software Suite GEO5 has been used for the relevant analysis.

Author Contribution Conceptualization: Duda; Data curation: Duda; Formal analysis: Duda; Funding acquisition: Siwowski; Investigation: Duda; Methodology: Duda, Siwowski; Project administration: Duda; Resources: Siwowski; Supervision: Siwowski; Validation: Duda, Siwowski; Visualization: Duda; Writing—original draft: Duda; Writing—review and editing: Siwowski.

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Data Availability Not applicable

Declarations

Additional Declarations for Articles in Life Science Journals that Report the Results of Studies Involving Humans and/or Animals Not applicable

Ethics Approval Not applicable

Consent to Participate Not applicable

Consent for Publication Not applicable

Conflict of Interest The authors declare no competing interests.

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