FACTA UNIVERSITATIS
Series: **Mechanical Engineering**
https://doi.org/10.22190/FUME230914041F

Original scientific paper

EVALUATION OF INNER SHEAR RESISTANCE OF LAYERS FROM MINERAL GRANULAR MATERIALS

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Abstract. *The methodologies used to assess the inner shear resistance of granular layers from minerals measured in the laboratory with and without geosynthetic reinforcing layers are described in this paper. For the measurements, a multi-level shear box is applied without considering vertical loads on the top layer. In the literature and engineering practice, an accepted calculation method for determining inner shear resistance exists. It is the shear force with linear shearing speed, primarily after a peak force value. This can be accounted for in the present case by calculating the average force value for the 40-80 mm shear range using previous scientific and research achievements. The article details each possible additional method and compares it different methods. Three granular materials, as well as six planar geosynthetics, were studied. For this purpose, the results of 216 measurements were considered and processed using 61 different shear function-qualification parameters. The calculations were performed using a simplified function fitting test and a selection process to maximize the allowable relative standard deviations. All three types of materials and four classification parameters were chosen as references for comparability. As a result, only one alternative parameter can be used to determine the reinforcing-weakening values with a maximum deviation of 5% while not producing insufficient results in the placement (ranking) of the individual granular material and geosynthetic pairings. This parameter is the area under the function (integral) calculated on the measurement graph of the 40-80 mm shear range, in kN×mm unit; it gives correct values only if the reference granular material is the considered railway ballast, the shearing plane is the geosynthetic's plane (i.e., the so-called "0-plane"), and the reference qualification parameter is the original recommended parameter. The best relative standard deviation values were 20% and 30%.*

Key words: *Planar Geosynthetic, Geogrid, Geotextile, Reinforced Granular Layer, Inner Shear Resistance*

Received: September 14, 2023 / Accepted October 28, 2023
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1. INTRODUCTION

People are traveling more and more, spending more of their lives on/with transportation, thanks to the industrial revolutions, globalization, and widespread urbanization [1,2]. This can include short trips within a residential area, but it can also be part of a longer daily commute for work, as well as work or tourist trips of several thousand kilometers. Rail transportation can be a competitive option in terms of speed, allowing for travel times, mainly, up to 1000 kilometers [3,4].

Railways have been an essential part of global transportation for nearly two centuries. Since the invention of the steam engine in the 18th century and then the steam locomotive in the 19th century, railways have left (and continue to leave) an indelible mark on the world by significantly influencing economic and technological development, social relations and, of course, environmental sustainability [5].

The development of railways marked a turning point in transportation history. Prior to the invention of steam locomotives, land transportation relied primarily on horse-drawn carriages and a primitive road network. The so-called "railway revolution," which began in 1825 with George Stephenson's locomotive (Locomotion), heralded a new era of public transportation. This transformation aided industrialization, urbanization, and commercial network(s) expansion [5].

When discussing railways, the concepts of dependability, punctuality, and efficiency are well-known [6]. They can transport a large amount of freight and many passengers at significantly lower ton-kilometer costs than other modes of land transport. Due to well-organized traffic and well-planned timetables, railways are less congested. Moreover, rail transportation is less affected by bad weather and traffic (and accidents); it is a dependable mode of transportation [6].

Some countries and railways take great pride in adhering to train timetables. According to EU statistics, Estonia and Latvia had the highest passenger train punctuality (around 99%) in 2018 [7]. Denmark, Finland, and Sweden had 95% accuracy rates, while Hungary had 78.41%, compared to the EU average of 90.21% [7].

One of the least polluting modes of land transportation is railway transportation. Trains produce fewer greenhouse gases per kilometer than trucks and automobiles [8,9]. At the same time, the energy required to run and operate trains (including traction, acceleration, and comfort) is among the most affordable modes of transport [8-11]. Electric rail systems powered by renewable energy sources can further reduce carbon emissions, assisting with global climate change efforts. In this regard, green energy is critical, and it is important to note that this is not only energy consumption but also energy production and storage. Battery power is frequently used as an option in the case of electric rail systems [12]. In any case, everyone must think globally in terms of entire life cycles, i.e., people should not look only at end-users with the trendy slogan of 'zero emission'.

Rail transportation is one of the safest modes of transportation compared to other modes [13,14]. Accidents are reduced by the isolated – albeit faster – track and strict safety standards and adherence to them [15]. To improve passenger and freight safety, modern trains employ advanced safety technologies such as automatic braking systems [16]. Given the impact of risk events on infrastructure project costs, timeliness, and quality, risk management investment is required to avoid or mitigate negative consequences [17]; decision-making analysis is critical and crucial in this field [18].

Railways can also transport large quantities of cargo such as coal, iron ore, cereals, and other raw materials (an Australian example [19] shows the transport of iron ore in the north-west of Australia in 2011-2012, with a transport demand of 510 million tons/year). Another Australian example [20] compared coal transport prices by road and rail, with an official statistic from 2005 showing a 2:1 ratio per tkm net (tkm means ton-km), or roughly 6:3 AUD cents. In addition, an interesting graph highlighting these transportation costs from 1964 to 2001 was provided. It is fascinating to see how, around the mid-1980s, prices shifted from favoring road transport to favoring rail transport. As a result, transportation costs can be significantly reduced, which benefits industries that rely on bulk transport.

Railways can reduce road congestion by diverting a significant portion of freight traffic from highways, i.e., from general road freight traffic [21]. Danielis and Marcucci [21] show the total costs of congestion for road and rail transport under three scenarios, including congestion charges and political-institutional changes. This reduces not only traffic congestion but also road infrastructure maintenance costs.

Along with the above advantages, railways have some disadvantages, which will be discussed further below [6].

One of the significant disadvantages of railways is their limited access [22]. Rail networks may not reach all remote or rural areas, posing transportation challenges in areas with insufficient rail coverage. Alternative modes of transportation, such as trucks or ships, are required to cover the "last mile" in these cases.

Rail systems, by definition, are less adaptable than road systems. Butko et al. [23] discuss railway door-to-door transport options, Shkurina and Maskaeva [24] discusses rail transport inflexibility and penalties for noncompliance with contracted delivery times. Shkurina and Maskaeva [24] also discuss identifying systemic "breaches" in the quality of the transportation process and measures to improve the quality of transportation services provided to customers. This inflexibility could harm industries that rely on "agile" supply chains or serve niche markets.

Construction and maintenance of rail infrastructure is expensive and is frequently financed by governments or private investors. Rail may be less appealing in the short term due to the relatively long payback period for these investments, especially when compared to more cost-effective road transport options. Carteni and Henke [25] calculated a benefit-cost ratio of at least 2.0 and a payback period of at least 15 years for the Formia-Gaeta tourist rail line in Italy.

While railways are ideal for transporting large amounts of freight, they may not be the most expedient option for time-sensitive shipments [24]. Fast-moving industries, such as perishable goods [26] or time-critical manufacturing, are less well-suited to rail transportation. Trains have a maximum speed limit determined by the vehicle's technical parameters and track speed. Although freight train schedules can be planned to some extent, rail companies generally prefer passenger trains to run first (freight trains are "put on hold" and must wait longer in traffic jams), so delivery times are less predictable than for road transport. In most cases, this precludes them from being used for time-sensitive deliveries. A freight wagon may pass through several marshaling yards on a long journey, where it is reassigned to different trains based on its destination. All this takes time, which increases the distance traveled between the point of dispatch of the freight/wagon and the destination. Freight trains are frequently run at night to avoid interfering with the heavy passenger train traffic during the day.

Environmental protection and awareness have been demonstrated to be increasingly important in protecting our planet, and it is worthwhile to implement as many environmentally friendly technologies as possible in all aspects of life [27]. To ensure the future of people's survival and health, we must consider reducing the high share of personal car transportation in the modal split or shifting to a significant use of green fuels, possibly even renewable energy sources. Public transportation, personal (traditional or electric) bicycle transportation, e-rolling, and so on, shift the modal split in the right direction for shorter travel distances. It is easily solved by widespread adoption and preference for "car-sharing" services, but public transportation should be made more appealing by introducing discount programs and other similar solutions. In this case, rail transportation should be preferred over road transportation because it is more environmentally friendly. Needless to say, opportunities, such as electric vehicle transportation, must be considered. They will become an increasingly important part of land transport in the future, both for passenger and freight transport. There is some hope in the freight sector that RoLa trains, which have lagged for many years, will resume their essential role in freight transport.

Significant financial resources (foreign subsidies and domestic capital) are required to build high-quality railway infrastructure and purchase modern fleets to achieve these goals as soon as possible. If the described scenario is realized, the economic implementation of new construction, rehabilitation reconstruction, and a significant reduction in the number of maintenance interventions will be critical in the field of rail infrastructure. Moreover, modern building materials and technologies will be essential.

It should be noted that Hungary received over one trillion HUF (Hungarian Forint, 1 HUF equals approximately 0.0025 €) in EU support for railway and urban rail development during the 2014-2020 EU cycle, which contributed to significant improvements in the country. Modernization of the Hungarian track design regulations (unfortunately, in parts, there are more than 30-year old regulations [28]) and widespread use of the established "e-rail system" will be required in the future because track design speeds for these are not more than 160 km/h – of course, in the relevant new harmonized European standard [29], it is possible to find design parameters that can also be applied to speeds of 300 km/h. The second most important aspect is that according to the theory of railway track degradation [30,31], someone must keep our railways in good technical condition during the current EU financing cycle (2021-2027) and in the future, taking into account that the expected lower amounts are to be spent on track rehabilitation because our high-quality reconstructed lines may face a similar fate without maintenance and maintenance funds as they did in the 1990s and 2000s.

The author wanted to emphasize the development of the scientific and research discipline of civil engineering and transport sciences with the above paragraphs, especially on the socio-economic environment (for detailed information, see Section 2).

According to the paper, one of the most common causes of railway track geometry failures is the poor, inadequate condition of the railway substructure, low load-bearing capacity, drainage problems, and so on [32]. Short and long sections can both benefit from geosynthetic reinforcement. This can be done in a variety of ways. For example, a granular layer was added on top of the substructure, i.e., beneath the crushed stone railway ballast. This layer and its lower plane may contain one or more planar geosynthetic layers supplemented by a geotextile layer. The other option is to directly place planar geosynthetic material beneath the crushed stone railway ballast to specifically and primarily geometrically stabilize it (i.e., the railway track itself). In this paper, the author examines how geosynthetic reinforcement affects the inner shear resistance of granular materials applied in transport infrastructure facilities. For this purpose, several granular materials and planar geosynthetics were tested in a multi-level shear box under laboratory conditions [8]. Based on the previously demonstrated applicability of the multi-level shear box, the main goal of this paper is to investigate how shear functions can be used to determine classification/qualification values/parameters for each shearing plane. There were 216 measurements taken in total. The author's aim was to search for new function-qualification parameters that could replace the 2012 evaluation option [8].

The structure of the paper is the following: Section 2 is a detailed literature review, Section 3 is about materials and methods, Section 4 is the discussion section, and Section 5 is where the author summarizes the main findings of the study.

2. Problem Statement and Further Literature Review

The required thickness of the granular layers needs to be applied and installed, as well as the value of the (increased) load-bearing capacity available with them, is a national economic issue in the maintenance, renovation (rehabilitation), and modernization of newly constructed, as well as existing railway facilities [8,9]. This is especially important in low-load-bearing capacity subgrades. Granular materials don't have enough tensile and shear strength, but they can be supplemented with geosynthetic materials (typically geogrids). This type of geogrid reinforcement property is known as interlocking effects – with some exceptions for geotextiles and geomembranes; for example, reinforcements can be achieved at least to a limited extent in the foundation of soil earthwork with high friction because they can be removed from the load with potentially significant elongation (deformation), this is known as a membrane effect [33,34].

The behavior of this interaction under relatively small displacements, when the elongation of the geogrid is no more than 1%, demonstrates the practical usefulness of the interlocking effect. In this case, the interlocking effect of the geogrid on the subsoil and the granular layer – i.e., the formation of a "composite layer" of the geogrid and granular layer – provides lateral support, thereby reducing vertical load deformation.

The use of the geosynthetics (geogrid and geotextile), mentioned above, in the layer structure can also ensure the required load-bearing capacity value with a thinner granular supplementary layer. Geogrids with specific parameters can be placed directly beneath the ballast bed to stabilize track geometry in railway construction. Geosynthetics are also used in the construction of reinforced retaining walls, abutments, and other "ground reinforcement" (or "ground reinforcing") structures.

The inner shear resistance of granular materials could be determined using a special multi-layer box, with the distance above the geosynthetic plane becoming the determining factor [8]. The behavior of geogrids on railway tracks could be evaluated by constructing experimental sections and monitoring them over time [35], it won't be covered in detail.

Geosynthetics are classified into the following categories: (i) geogrids, (ii) geotextiles, (iii) geocells, (iv) geonets, (v) geopipes, (vi) geofoam, (vii) geocomposites, and (viii) geomembranes. The types under consideration are (i) and (vii), where the relevant geosynthetic types are geogrids combined with geotextiles in the case of geocomposites (vii).

Geogrids are engineered polymer materials formed from polyethylene, polypropylene, polyester, and other polymers designed to improve the mechanical properties of soil or granular materials. They are available in various shapes and sizes, such as woven, knitted, extruded, and welded grids, each tailored to a specific application. Geogrids work by confining and distributing applied loads, reducing lateral movement, and increasing the underlying soil or granular material's load-bearing capacity.

Dynamic loads from trains that vary in weight (axle load and train length), speed, and frequency are applied to railway tracks [36-38]. If not properly managed, these loads significantly stress the underlying ballast and subgrade layers, resulting in track deformation, settlement, and even failure. Traditional ballast materials like crushed stone or gravel have limited load-bearing capacity and relatively poor long-term performance.

Geogrids increase the load-bearing capacity of granular layers beneath railway tracks significantly. Geogrids' confinement and reinforcement distribute loads more evenly, lowering the risk of track deformation and settlement. This allows heavier trains to pass and ensures the railway infrastructure's long-term stability.

Geogrids also improve track stability by preventing lateral movement of ballast material. This reduces track misalignment and keeps the tracks in place, requiring less frequent realignment and maintenance.

Granular layers reinforced with geogrids can extend the life of railway tracks. They reduce deformation and settlement, which reduces wear and tear on track components such as ties and rails. As a result, railway infrastructure is more long-lasting and cost-effective.

The improved performance and longevity of geogrid-reinforced granular layers result in lower maintenance costs. Fewer disruptions, fewer track repairs, and lower operational costs over time benefit railway operators.

The material and type of geogrid used in the design of reinforced granular layers for railways are critical. The selection process should be guided by factors, e.g., anticipated traffic load, soil and environmental conditions. The effectiveness of geogrid reinforcement is dependent on proper installation. To ensure a stable and uniform track foundation, the granular material and geogrid layers must be carefully placed, and the layer must be compacted. A critical design parameter is the depth at which geogrids are placed within the granular layers. When determining the depth, the load requirements, soil conditions, and desired performance goals must be considered. In railway construction, effective (adequate) drainage is critical. To prevent water accumulation and maintain track stability, geogrid-reinforced granular layers should be designed to work with drainage systems.

Geotextiles are synthetic or natural fabric materials commonly used inside or below the layers (ballast, supplementary/protection layers) of railway permanent way. They serve many purposes in terms of improving the performance and durability of railway tracks.

Geotextiles come in both woven and non-woven varieties. Individual yarns are woven together to form a fabric to produce woven geotextiles. They have a high tensile strength and are commonly used in railway applications for separation and reinforcement. Fibers are randomly arranged and bonded to create non-woven geotextiles. They are frequently used in railway construction for filtration and drainage.

Geotextiles are designed to withstand the loads and stresses imposed by trains and the surrounding materials. The second most important feature is their permeability. Geotextile permeability varies and can be tailored to meet specific drainage and filtration requirements. Geotextiles are designed to withstand environmental factors, such as moisture, UV radiation, and chemical exposure. Geotextiles are easy to install in various railway applications due to their flexibility and adaptability.

Geotextiles act as a barrier between soil or aggregate layers, preventing intermixing and preserving each layer's integrity. This separation function is critical in preventing ballast and subgrade material contamination. They can improve subgrade soil load-bearing capacity by distributing loads more evenly. This is especially useful in areas with poor or unstable soil. Owing to the fact that they allow water to pass through while retaining soil particles, non-woven geotextiles are commonly used for filtration. This helps to keep the drainage system clear and the track structure's hydraulic performance intact. Water can flow through geotextiles, lowering the risk of water accumulation and track deformation. They can stabilize embankments and slopes, preventing erosion and preserving the railway alignment's integrity. Since geotextiles improve track structure stability, they can reduce maintenance requirements, operational costs, and rail service disruptions.

Geogrids and geotextiles are used together in the category (vii) above (of course, different types of geosynthetics from the list can also be combined). The general idea is that geocomposites combine the benefits of geosynthetics. The author refers to geotextile-combined geogrid as a geocomposite for the rest of the article.

Using geosynthetic-reinforced granular layers in railroad construction has both positive and negative environmental consequences. On the plus side, these reinforced layers reduce the need for frequent maintenance and track repairs, potentially causing less disruption to local ecosystems and requiring less energy for maintenance activities. Furthermore, the increased life of track service can help reduce material consumption and the environmental impact of track replacement. On the other hand, the environmental impact of geogrid production and disposal must be considered. The production of geogrids necessitates the use of energy and raw materials. The industry emphasizes recycling and using sustainable materials in geogrid manufacturing to counteract these effects.

The received reinforcement solutions help strengthen and stabilize granular layers in transport construction when geosynthetic layers are incorporated underneath or within granular layers; these applications are discussed in this paper. Several areas are mentioned in the international literature on granular materials reinforced with geosynthetics. In addition, many new findings have been published in the last 30 years.

Today, the most suitable research methods in this research area are (i) laboratory tests with shear box [39], triaxial tests [40], shear wave measurements [41], large-scale testing facilities [42], other laboratory tests (e.g., pull-out and/or dynamic tests, geogrid mechanical tests); (ii) field testing [33,35]; (iii) computer simulation using finite element method (FEM) [43] and discrete element method (DEM) [40]. The FEM's other application can also be found in engineering studies [44-46].

Planar geosynthetics, such as geogrid and geotextile, have become common building materials in railways. Geogrids installed directly beneath railway ballast can stabilize the geometry of the railway track, extending the time interval between geometric adjustments significantly. The crushed grains are wedged (wedged) into the geogrid opening and held together by the geogrid's ribs or bands (see Fig. 1 [33,34]). These 'fixed' grains connect the grains in and above this plane. This results in the formation of a quasi-strong and relatively slip-free layer. For example, laboratory and field studies have demonstrated geogrids' effectiveness in reducing subsidence (deformation) and ballast degradation [34,47].

Placing a geogrid layer in the granular layer can improve the layer structure's inner shear resistance and bearing capacity [48]. However, the mechanism of grain-geogrid interaction is not fully understood.

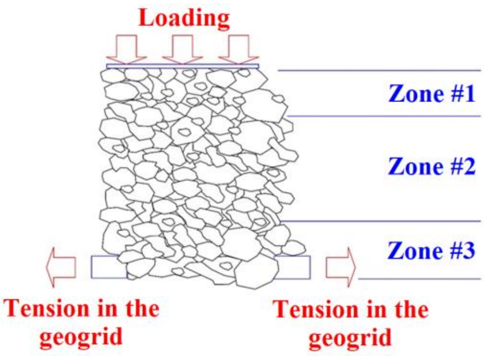

Fig. 1 The zones of the interlocking effect in a granular material due to a planar geogrid layer (on the basis of [33,34])

3. Materials and Methods

When choosing a geogrid product, especially in the design phase, an important question is, which parameters are essential, i.e., which parameters significantly influence the interlocking effect?

The quality characteristics required by the related EN standard [49] are as follows:

- tensile strength in the longitudinal and transverse direction, the applied unit is kN/m [50];
- longitudinal and transversal elongation (approx. strain) at maximum load the applied unit is % [50,51];
- stiffness at 2%, 5%, and 10% (relevant to specific conditions of use);
- tensile strength of seams and joints (only relevant for geocomposites, geotextiles related to specific conditions of use);
- static puncture resistance (only relevant for geocomposites, geotextiles) [52];
- dynamic perforation resistance (only relevant for geocomposites, geotextiles) [53];
- durability [49];
- another parameter, specifically related to special conditions of use (they can be neglected in the first instance.

Although the reinforcement function standard specifies the five characteristics that should be included in every geogrid's performance declaration, experience has shown that other relevant parameters should be taken into account when determining a product's effectiveness. According to practical research, the grain structure composition of any granular soil has an optimal aperture size at which the interlocking effect is most significant [8,48]. According to other research, tensile stiffness at low elongations, nodal stiffness, aperture shape, geogrid thickness, fabrication technology, and other factors all influence performance [33,34,54].

The laboratory experiments were carried out as described in [8,48] in the Structural Testing Laboratory of Széchenyi István University (Győr, Hungary) with 31.5/63 mm "E type" railway ballast (RB) from andesite [55], CSBCG 0/56 crushed stone (andesite railway protection layer) [56] made of andesite crushed stone particles, as well as CGM1 [57] granular railway supplementary layer (made from andesite and quartz sand with mixing). The CSBCG is the crushed stone base layers with continuous grading; CSBCG 0/56 is used for the abbreviation (in Hungary, the FZKA 0/56 abbreviation is also applied). The CGM1 is a granular railway sub-base layer material (CGM stands for coarse grain mixture; in the original German regulation, Ril. 836 [58], it is referred to as KG, i.e., "Korngemisch"). CGM1 is a quasi-waterproof material and CGM2 is a quasi-water-permeable layer; in Hungary, the SZK1 and SZK2 [57] abbreviations are applied for CGM1 and CGM2 materials. Table 1 contains the relevant details of the executed three test series.

Table 1 The details of the conducted three test series

No. of tests	Details of the test
Test #1	The filling material was RB, without geogrid and with five different geogrid types: • geogrid type #1 (GG1); • geogrid type #2 (GG2); • geogrid type #3 (GG3); • geocomposite type #1 (GC1); • geocomposite type #2 (GC2).
Test #2	The filling material was CSBCG 0/56, without geogrid and with four different geogrid types: • GG1, GG2, GG3, GC1.
Test #3	The filling material was CGM1, without geogrid and with six different geogrid types: • GG1, GG2, GG3, geogrid type #4 (GG4); • GC1, GC2.

One test series consisted of the following measurements:

- one type of elastic sublayer was taken into consideration (E_2=7.2 MPa) [59];
- layer construction on elastic sublayer: geogrid/geocomposite + 0.4 m granular material, i.e., RB or CSBCG 0/56 or CGM1;
- only compacted state was considered, the compaction was applied on the +0.20 m and +0.40 m height planes, the details of the compaction are described later in Section 3;
- no vertical pressure was applied on the top surface of the layers;
- measuring of the inner shear resistance of the layer structure (horizontal pushing force) in four different planes (on the plane of geogrid, i.e., +0.00 m, +0.10 m higher, +0.20 m higher, and +0.30 m higher);
- each case was measured three times.

The number of the required measurements:

- in Test #1: 4×6×1×3=72 (i.e., 4=four shearing planes; 6=without geogrid and five geogrid types; 1=compacted filling material; 3=three times repeat);
- in Test #2: 4×5×1×3=60;
- in Test #3: 4×7×1×3=84;
- altogether: 72+60+84=216.

In all cases, the three-three measurements were conducted for each set-up to characterize the inner shear resistance of the considered assemblies on all the shearing planes.

RB and CSBCG 0/56 type protection layer materials were transported from the Szob quarry of Colas Északkő Kft., which are in accordance with all the related standards [55-57]. The CGM1 type granular protection layer material was mixed in the laboratory, except for 0/1 mm fraction (sand); every fraction was transported from the same quarry as CSBCG 0/56 and RB. Except for 0/1 fraction (quartz sand), all the materials were andesite. The grain size distribution curves of measured granular materials were as follows: RB [8], CSBCG 0/56 [48], and CGM1 [57]. In the case of CGM1 the quarry precisely set the particle size distribution curves to the mean values between the lower and upper borderlines. The requirements and applied values are shown in Tables 2 and 3.

Geosynthetics were chosen for the test series according to the fact that their short-term tensile strength (considering the reduction factor) would be the same, so they can be compared:

- GG1: Polypropylene (PP) raw material welded junction geogrid, the aperture size was 44×40 mm – biaxial geogrid that was from stiff, preloaded, extruded PP hanks, in both directions with the same design strength value, junctions were made by computer-aided laser welding.
- GC1: The GG1 geogrid with 160 g/m^2 mass PP non-woven geotextile.
- GG2: PET (polyethylene terephthalate) raw material woven geogrid with PVC (polyvinyl chloride) coat, the aperture size was 35×35 mm – biaxial woven geogrid that were from PET piles with post-made PVC coat.
- GC2: The GG2 geogrid combined with PET non-woven geotextile.
- GG3: PP raw material extruded geogrid, the aperture size was 39×39 mm – extruded geogrid manufactured by stretching the punched sheet of PP in two orthogonal directions.
- GG4: PP raw material extruded geogrid, the aperture size was 34×34 mm – extruded geogrid manufactured by stretching the punched sheet of PP in two orthogonal directions.

Table 2 Particle size distribution requirements for the RB material and the applied values [55]

Granular materials/Sieve size [mm]	**Percentage passing by mass – RB lower boundary line**	**Percentage passing by mass – RB upper boundary line**	**Applied percentage values [8]**
22.400	0.00	3.00	0.52
31.500	1.00	25.00	1.43
40.000	25.00	75.00	33.89
50.000	55.00	90.00	66.34
63.000	95.00	99.00	98.80
80.000	100.00	100.00	100.00
31.500 to 63.000	≥50.00		>97.00

Table 3 Particle size distribution requirements for the CSBCG 0/56 and CGM1 materials standards, and the applied values [55-57]

Granular materials/ Sieve size [mm]	Percentage passing by mass – CSBCG 0/56 lower boundary line	Percentage passing by mass – CSBCG 0/56 upper boundary line	Applied percentage values – CSBCG 0/56 [48]	Percentage passing by mass – CGM1 lower boundary line	Percentage passing by mass – CGM1 upper boundary line	Applied percentage values – CGM1
0.063	0.00	7.00	4.00	0.00	7.00	3.50
0.125	2.00	10.00	6.20	7.00	17.00	12.00
0.250	3.00	14.00	8.40	15.00	31.00	23.00
0.500	5.00	18.00	12.60	23.00	43.00	33.00
1.000	7.00	25.00	16.50	31.00	51.00	41.00
2.000	10.00	32.00	24.20	40.00	60.00	50.00
4.000	15.00	40.00	39.70	50.00	70.00	60.00
8.000	22.00	50.00	49.50	62.00	82.00	72.00
16.000	35.00	65.00	59.10	75.00	92.00	83.50
32.000	55.00	85.00	72.20	86.00	100.00	93.00
56.000	90.00	99.00	93.50	n/a	100.00	n/a
63.000	100.00	100.00	99.70	96.00	100.00	98.00
80.000	100.00	100.00	100.00	100.00	100.00	100.00

The relevant physical and mechanical characteristics of the geogrids and geocomposites can be seen in Table 4.

Table 4 Physical and mechanical characteristics of geosynthetics

Geosynthetic types/Characteristics of the geosynthetics	**GG1** and **GC1**	**GG2**	**GC2**	**GG3**	**GG4**
Raw material	PP	PET+PVC	PET	PP	PP
Production method	welded	woven	woven	extruded	extruded
Tensile strength at 1.0% elongation [kN/m]	7.0	n/a	n/a	n/a	n/a
Tensile strength at 2.0% elongation [kN/m]	12.0	~8.0	~8.0	10.5	10.5
Aperture size [mm×mm]	44×40	35×35	35×35	39×39	34×34

In addition, the author does not wish to go into more detailed information on the geosynthetics used because the goal of the current study is not to classify individual geosynthetics but only to provide a calculation method that could be used to substitute or replace those previously employed, and possibly to provide a means of controlling them.

The multi-level shear box test was first published by Fischer [8].

The area of the shear box is 1.0×1.0 m, the height is also 1.0 m, and it has a frame that consists of 10 pieces. The frames are made of steel U-profiles and are fixed to each other by M12 screws, except at the plane of shearing. The structure of the box allows for the shearing plane to be set at different depths in the box.

The box part under the shearing plane moves on cylindrical rolls on the flooring of the laboratory if there is a horizontal pushing force. On the opposite side of the box, the counter force has to be actuated over the shearing plane. This force can keep the upper part of the box immobile (Fig. 2).

During the tests, counter and pushing forces are recorded simultaneously. These two forces should be the same because the movement of the box's lower part must be expected. If the difference between the counter and pushing force is more than 10%, the measurement must be repeated. The published results do not contain values with the mentioned error.

The test starts at shearing plane No. 4 (top) and follows the planes No. 3, No. 2, and No. 1 (Fig. 3). The shearing speed is 1.5 mm/s. The maximal displacement of the frames is approximately 80 mm, and it does not influence the particles' position in the planes below the shearing plane.

On both sides of the box (parallel to the shearing direction) in the upper five frames are windows made of plexiglass with 200×60 mm dimensions. Through these windows, the possible movement of crushed stone particles can be monitored during shear tests. It can be determined whether there is any particle movement and/or rotation of particles over and/or under the shearing plane.

Due to the shearing (mainly in the case of shearing in the shearing plane No. 4), the particles raise the upper frame; in this way, a vertical force is needed onto the upper frame. This force does not influence the inner shear resistance because it does not act onto and into the granular material.

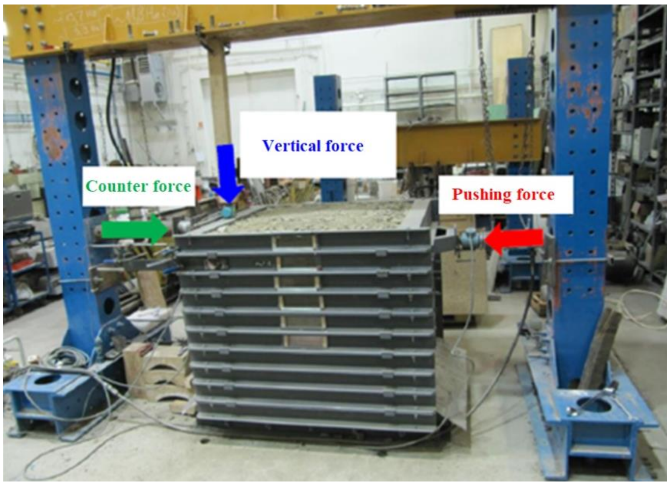

Fig. 2 The measuring principle of the multi-level shear box [8]

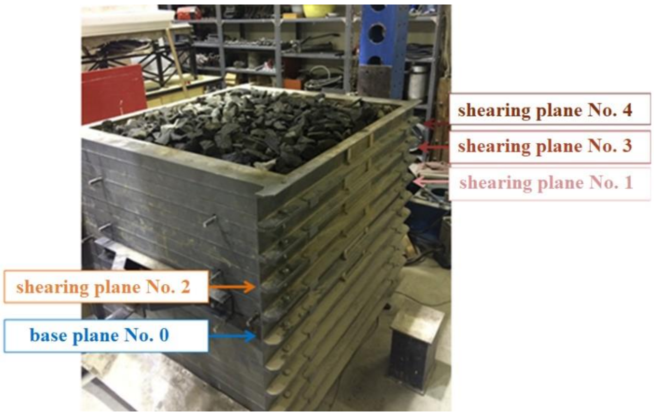

Fig. 3 Marking of shearing planes [8]

Before the tests, the friction resistance values between the frames were measured [8]; they were considered negligible values during the evaluation of the test series.

The lower part of the box (under the shearing plane) should be filled with elastic material with low load-bearing capacity. Material such as Thermopan XPS plates could be used. The E_2 modulus of this layer should be determined with a static load plate test. The elasticity of the elastic supporting layer can be modified if its thickness increases or decreases. The reinforced concrete floor of the laboratory and steel plates used in the bottom of the lower frame of the box do not influence this value because of their approximately infinity elasticity. The low value of load-bearing capacity (E_2 modulus 5…15 MPa) can be achieved using Thermopan XPS sheets with 40…50 cm thickness.

The static E_2 modulus, which can describe the load-bearing capacity of the support layer, was determined according to the Hungarian Standard MSZ 2509-3:1989 [59]. The bearing capacity was calculated according to [59] is E_2=7.2 MPa. This means it was a significant weak support.

The second layer from the bottom was sand with 10 cm thickness, laid on a geotextile layer. This layer helped the crushed stone particles penetrate into the aperture of geogrid and protects Thermopan XPS sheets against the sharp edges of crushed granular stone/mixture.

One layer of geogrid or geocomposite (geotextile+geogrid) was laid on the top of the sand layer.

Ensuring quasi-same circumstances in the same measurement series was very important. It meant that in every test series, the compaction level of ballast was the same, but there was no such apparatus with which the density of the applied granular material could be measured in the shear box. In this way, the following things had to be done:

- always the same compaction apparatus was used;
- always the same number of compaction passes was utilized.

The compaction tool's (Fig. 4) main parameters were as follows:

- mass: 68 kg;
- power output: 1.1 kW;
- nominal vibrating frequency: 3000/min;
- platform: 500×500 mm.

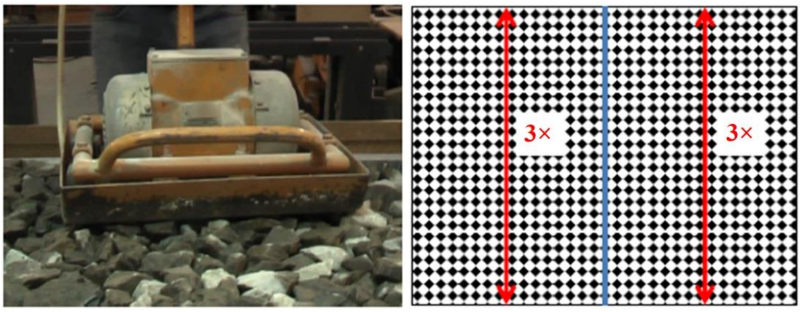

Fig. 4 Vibrator compaction tool and compaction processions

The granular materials were compacted (Fig. 4) in two layers, at 20 cm and 40 cm height. One compaction meant that on each occasion on two traces, there were three processions.

One test series consists of altogether four shears: on the shearing planes No. 4, No. 3, No. 2, and No. 1.

Test series were conducted in the Széchenyi István University's laboratories, where granular protection layers (CSBCG 0/56 and CGM1) and railway ballast (RB) were investigated.

The constant parameters were the following:

- E_2 modulus of the support layer under the geogrid: E_2=7.2 MPa;
- thickness of the sand layer: 10 cm;
- one layer geogrid, or one layer geocomposite;
- thickness of the granular material in the shear box: 40 cm;
- only compacted materials: compaction on two layers: on the +0.20 m and +0.40 m height;
- number of shearing planes: 4;
- no vertical pressure.

The test series enabled the determination of the inner shear resistance curves in function of the distance from +0.00 m height plane. In the current paper, the aim was not to directly determine these functions; however, it was to find the definition of the possible alternative calculation methodologies – i.e., other parameters and/or characteristics of the shear graphs, etc.

The instruments used for laboratory experiments are detailed in Tables 5-7.

The load was applied with a HI-FORCE brand oil-pumped hydraulic work cylinder. The applied sampling frequency was 5 Hz, and the shearing speed was set to approximately 1.5 mm/s.

Table 5 The load gauge instruments applied for the tests

Designation and manufacturer/type	The average value of measurement error
Load gauge HBM W100K	40 kN – 0.10% 100 kN – 0.15% 200 kN – 0.20% 400 kN – 0.30 %

Table 6 The LVDTs (Linear Variable Differential Transformer) applied for the tests

Manu-facturer	Type	Serial No.	Measuring range	Output signal	Sensiti-vity	Zero shift	Resistance
HBM	W20TK	6950	±20 mm	80 mV/V	±1.0%	<±0.05%	10 mH; 56 Ω
HBM	W20TK	6951	±20 mm	80 mV/V	±1.0%	<±0.05%	10 mH; 56 Ω

Table 7 The applied test instruments

Instrument (type, IDs, etc.)	Special characteristics
Amplifier: Hottinger SPIDER8, 8-channel measuring amplifier	accuracy: 0.1%
Module: SR55	accuracy: 0.1%
Software: CATMODUL 5.0	
Computer: COMPAQ Armada 100S	

The details of the evaluation methodology are summarized in the following list:

- 61 different function qualification parameters were defined and calculated individually for all measured shear graphs (see Fig. 5);
- the 61 parameters (characteristics) were defined in such a way that the exact points of the shear functions could be clearly and easily identified in the subsequent analysis;
- for each parameter, the mean, the standard deviation (SD), and the relative standard deviation (RSD) values for each shearing plane were calculated;
- RSD: 10%, 20% and 30% were considered;
- reference materials were: RB, CSBCG 0/56, CGM1;
- four types of reference rating parameters were: #1, #21, #51 and #61 from the next list (i.e., Table 8);
- all four shearing planes were calculated individually;
- these could be calculated by defining ratios (the case of the reference material without geogrid reinforcement was 1.0 for the defined reference function parameter);
- 1%, 2%, and 5% allowed deviations from the reference value (i.e., from the specified ratio values, to be more precise), only the given pair of values was compared and maximized the absolute value of the difference between them for this calculation (i.e., it was not considered which value is greater when formulating and applying this condition);
- Only cases in which the specified conditions were met for all cases (i.e., for all 17 other measurement series in addition to the specified reference) were considered suitable results, this was necessary because the 18 different granular material-geosynthetic pairs were relatively few for deriving global, completely general results, and only if all of them were met it could be claimed that the results obtained were suitable and acceptable.

Fig. 5 illustrates a typical shear curve (function) measured in the laboratory.

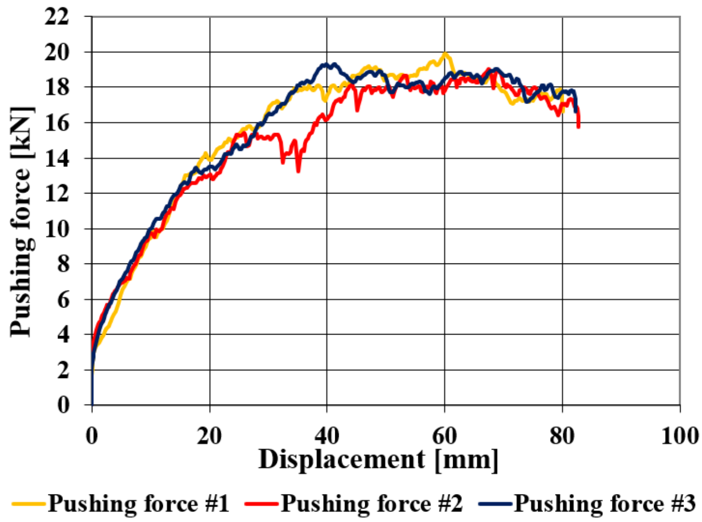

Fig. 5 A typical shear graph (curve) with the three repetitions of the measurement (RB without geosynthetic reinforcement, shearing plane #2, i.e., 10 cm above the geosynthetics' theoretical plane)

In all cases, the curves were recorded up to a minimum shear length (displacement) of 80 mm, the length that the multi-level shear box used and the design of the measuring system (i.e., mainly the hydraulic cylinder) allows.

The 61 qualification parameters are detailed in Table 8. All the parameters can be identified in Fig. 5.

It is worth mentioning that all the calculations were conducted by MS Excel. In the case of linear regression functions, only the tangent values were taken into consideration; however, the acceptable coefficient of determination value (R^2) was reduced to 0.7. In calculating integral values, numerical integration was applied, which meant that the rule and methodology of area determination by trapezoid calculation was used (a more complicated method was not needed because all the coordinates were known for every point). The tangent of the chord (chord modulus) was computed by simply dividing.

4. Results

As mentioned before, the calculations were carried out from the analysis of 216 shear graphs and 61 different qualitative parameters calculated for each of them, using as reference the three granular materials and the four different reference grading parameters. The calculations were carried out in MS Excel. For clarity of results, the calculations were performed systematically on separate spreadsheets and in several Excel files to avoid possible calculation errors and mix-ups. All the calculations, including setting up Excel worksheets, controlling them, and assessing the results, took about three working weeks.

Table 8 The details of the considered qualification parameters

No. of qualif. param.	Meanings of qualification parameters
#1	Global maximum value interpreted on the full shear graph, in kN unit.
#2	The calculated chord modulus (i.e., the tangent of the inclined straight line drawn between the force value for the shear length, or in other words, displacement) in kN/mm unit over the shear range 0-10 mm.
#3	The tangent of the linear regression function fitted to the measured values of the shear range (displacement), 0-10 mm, in kN/mm unit.
#4	The area under the shear function (integral) calculated on the measurement graph of the shear range (displacement) 0-10 mm, in kN×mm unit.
#5 – #46	See points #2 – #4 above, except when they are related to the shear ranges as follows: • 0-20 mm (#5 – #7); 0-30 mm (#8 – #10); 5-10 mm (#11 – #13); 5-20 mm (#14 – #16); 5-30 mm (#17 – #19); 5-40 mm (#20 – #22); 10-20 mm (#23 – #25); 10-30 mm (#26 – #28); 0-40 mm (#29 – #31); 15-30 mm (#32 – #34); 15-40 mm (#35 – #37); 20-30 mm (#38 – #40); 20-40 mm (#41 – #43); 25-40 mm (#44 – #46). The orders in the above rows themselves are the same as for points #2 – #4.
#47	The average force value calculated on the measurement graph of the 40-60 mm shear range, in kN unit.
#48	See point #4, except when it is related to the 40-60 mm shear range.
#49 – #60	See points #47 – #48 above, except when they are related to the shear ranges as follows: • 40-70 mm (#49 – #50); 40-80 mm (#51 – #52); 45-80 mm (#53 – #54); 50-80 mm (#55 – #56); 55-80 mm (#57 – #58); 60-80 mm (#59 – #60). The orders in the above rows themselves are the same as for points #2 – #4.
#61	See point #47, except when it is related to the entire shear range 0-80 mm.

It should be noted that only those results were accepted for which all (i.e., relative to the reference) the 17 measurement series gave a satisfactory result. As a partial result, those cases where acceptable results were obtained for each material (RB, CSBCG 0/56, and CGM1) individually could be used subsequently. However, these were not published in this paper because they are of considerable length and it is challenging to present them in a systematic way.

The main results can be summarized in the following. Tables 9 and 10 contain the cases and the parameters in which the first evaluation process gave an appropriate match. *Ref. RB_ref. 40-80 mm* means that the reference granular material is the considered railway ballast (RB) and the calculated qualification parameter is #51; see Table 8. *Ref. RB_ref. max.* means that the reference granular material is considered railway ballast (RB) and the calculated qualification parameter is #1; see Table 8). In *i_RSDj*, *i* refers to the shearing planes (i.e., *0* means shearing plane No. 1, and *30* means shearing plane No. 4, respectively), where the vertical distance of the planar geosynthetic layer and the shearing plane is 0-30 cm; *j* is the allowed maximum relative standard deviation – when calculating the three shear graphs' parameters – which differs between 10% and 30%.

Table 9 The results related to *Ref. RB_ref. 40-80 mm* in the first evaluation process

Cases	Qualification parameters
0_RSD20	#1 with 5% accuracy; #47 with 5% accuracy; #49 with 2% and 5% accuracy; #50 with 5% accuracy; #52 with 5% accuracy; #53 with 1%, 2%, and 5% accuracy; #54 with 5% accuracy; #55 with 2% and 5% accuracy; #56 with 5% accuracy; #57 with 5% accuracy; #58 with 5% accuracy; #59 with 5% accuracy; #60 with 5% accuracy.
10_RSD20	#47 with 5% accuracy; #49 with 5% accuracy; #50 with 5% accuracy; #52 with 5% accuracy; #53 with 2% and 5% accuracy; #54 with 5% accuracy; #55 with 5% accuracy; #57 with 5% accuracy; #59 with 5% accuracy.
0_RSD30	All the parameters mentioned in *0_RSD20* and #58 with 5% accuracy.
10_RSD30	All the parameters mentioned in *10_RSD20*.

Table 10 The results related to *Ref. RB_ref. max.* in the first evaluation process

Cases	Qualification parameters
0_RSD20	#51 with 5% accuracy; #53 with 5% accuracy; #55 with 5% accuracy; #56 with 5% accuracy; #57 with 5% accuracy; #59 with 5% accuracy.
0_RSD30	All the parameters mentioned in *0_RSD30*.

A function fit test was carried out, which meant that:

- the parameters were sorted in an increasing numerical order by reference to the above grouping, separately, i.e., *Ref. RB_ref. 40-80 mm* (*0_RSD20*, *10_RSD20*, *0_RSD30*, *10_RSD30*) and *Ref. RB, ref. max.* (*0_RSD20* and *0_RSD30*);
- values where any element of the data series showed an incorrect reinforcement effect (ratio to the reference values greater than 1.0), while for the reference, the ratio was less than 1.0 (i.e., a weakening effect), and for the opposite, the parameter was considered inadequate;
- then a detailed mathematical, statistical fit test was performed on the remaining parameters.

The above gives only one suitable parameter, as follows (*Ref. RB_ref. 40-80 mm*; *0_RSD20*, as well as *0_RSD30*):

- #52 with 5% accuracy.

For comparison, the difference values between the values of the unique data points could be fulfilled considering the arrangement of the 18 values in a row. The differences calculated for the two data sets compared to the reference were as follows (*Ref. RB_ref. 40-80 mm*, *0_RSD20*):

- in the case of #52 with 5% accuracy, the maximum difference values are +0.612% and –0.031%; the details can be seen in Fig. 6.

These obtained differences regarding granular materials were appropriate and acceptable because of the inhomogeneity of granular materials and the relative uncertainty of the distribution of particles within a given volume. This meant it was impossible to create a design with perfectly and precisely the same (exact) location and position within the pile twice. For this reason, a maximum relative variance of 30% and a maximum deviation of 5% were considered in the calculations.

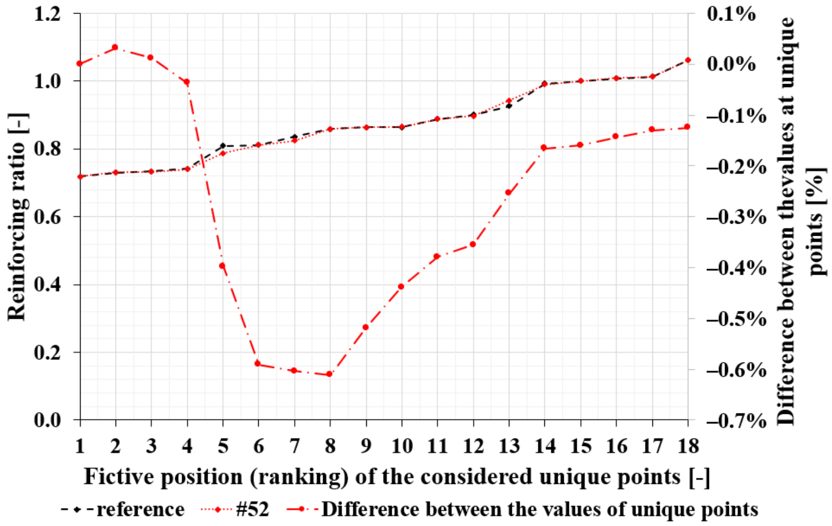

Fig. 6 Evaluation of the calculation by qualification parameter #52 in the case of *Ref. RB_ref. 40-80 mm* and *0_RSD20*

It was irrelevant considering the current paper's topic; however, the author decided to publish the meaning of the ranking in Fig. 6. The data are illustrated in Table 11. The first column contains the ranking based on Fig. 6, while the second column is related to the original identification number of the measurements.

Table 11 Meanings of the rankings in Fig. 6

Ranking based on Fig. 6	The original ID of the measurement	Meaning
1	12	CGM1 without geosynthetic reinforcement
2	10	CSBCG 0/56 with GC1 reinforcement
3	6	RB with GC1 reinforcement
4	7	CSBCG 0/56 without geosynthetic reinforcement
5	4	RB with GG2 reinforcement
6	18	CGM1 with GC2 reinforcement
7	3	RB with GG3 reinforcement
8	13	CGM1 with GG2 reinforcement
9	5	RB with GC2 reinforcement
10	9	CSBCG 0/56 with GG1 reinforcement
11	2	RB with GG1 reinforcement
12	17	CGM1 with GC1 reinforcement
13	11	CSBCG 0/56 with GG2 reinforcement
14	16	CGM1 with GG1 reinforcement
15	1	RB without geosynthetic reinforcement
16	15	CGM1 with GG4 reinforcement
17	8	CSBCG 0/56 with GG3 reinforcement
18	14	CGM1 with GG3 reinforcement

5. DISCUSSION

Based on the results written in Section 4, it should be pointed out that the results presented here are valid for the following limitations and should be considered together with them:

- to answer the question of whether the inner shear resistance qualification values averaged over a 40-80 mm section given in the Ph.D. thesis (see the qualitative parameter #51 above), it can be determined by a generally applicable method using a different function characteristic in such a way that the same reinforcing-weakening ratios were obtained as if determined by the method developed in 2012;
- the habilitation thesis in 2017 and several related papers [60] should be mentioned in which the tangent of the linear regression function fitted to the measured values of the shear range 5-40 mm, in kN/mm unit (see the qualitative parameter #21 above), noting that here the shearing plane No. 1 was considered; it was demonstrated through the detailed statistical analysis performed in this paper that the use of this parameter was not universal and cannot be accepted in all circumstances;
- it was also essential to be able to determine and eliminate which granular material was measured without a geosynthetic reinforcement, i.e., which one was chosen as the reference material;
- it was vital to highlight the following facts: three types of material, six types of geosynthetics (geogrid only and geocomposite) produced by three different production technologies were considered; this means that, although it was not possible to make a completely general statement for all granular materials and for all types of aperture sizes and materials, it should be noted that the other cases were likely to deteriorate the results and it was therefore necessary to verify the applicability of the method;
- the presented results do not imply that a parameter other than #52 cannot be used as a rating value for inner shear resistance, but it should be kept in mind that if a different rating parameter/characteristic was chosen, the results would not be comparable with the results from the qualification with #52;
- the results may vary depending on the sampling frequency and shear rate; therefore, the findings are mainly valid for the values presented in the article – a detailed analysis would need to be performed to disentangle the results from these characteristics/settings.

The results presented in Section 4 clearly show the following facts:

- only the RB material can be chosen as a reference, and only in the "0-plane" (shearing plane No. 1) will the results be correct;
- only acceptable results are obtained for relative standard deviations for 20% and 30%.

It should be mentioned that in the present study, the aperture size was in a relatively small range (34-44 mm), so the effect of aperture size could not be accounted for. Many geogrid types are available in the author's measurement database, so a more detailed study will be possible in the future. It should be noted that when considering a significantly larger number of samples, the need to define some acceptable maximum variance in the analyses arises. The author would like to point out here that for each calculation method, the permissible and acceptable calculation and prediction error (bias) to be taken into account should be specified.

6. CONCLUSIONS

The research focuses on the mechanics of granular materials used in transport infrastructure facilities (railways, roads, etc.), specifically the issue of load-bearing capacity for railway structures. It has been certified that achieving required load-bearing capacities with thinner granular supplementary layers is a matter of national economic importance.

The study shows that geogrid reinforcements, when used in combination with granular layers in railway construction, can provide adequate stabilization. This is especially useful in low-load-bearing capacity subgrades.

The study also discusses the practical utility of the interlocking effect between geogrids and granular layers in creating a "composite layer" that provides lateral support and reduces vertical load deformation.

The paper assesses the use of geosynthetics in this context, specifically geogrids and geotextiles. The use of these materials in the construction of special geotechnical structures (e.g., reinforced retaining walls and other ground reinforcement structures) is emphasized.

The paper describes the methodologies used in the laboratory to assess the inner shear resistance of granular layers from minerals applied for transport infrastructure facilities with and without planar geosynthetic reinforcement materials (i.e., planar reinforcing layers). A multi-level shear box was used without considering vertical loads for the measurements. In the literature and engineering practice, an accepted calculation method for determining inner shear resistance exists for the shear force with linear shearing speed, primarily after a peak force (resistance) value. In the present case, this can be accounted for by calculating the average force value for the 40-80 mm shear range using the author's Ph.D. thesis from 2012.

The article details each possible additional method and compares it with mathematical-statistical methods. Three granular materials (RB, CSBCG 0/56, and CGM1), as well as, six planar geosynthetics (GG1, GG2. GG3, GG4, GC1, GC2) were studied. For this purpose, the results of 216 measurements were conducted and processed using 61 different shear function-qualification parameters. The calculations were performed using a simplified function fitting test and a selection process to maximize the allowable relative standard deviations. All three types of materials and four classification parameters were chosen as references for comparability. As a result, only one alternative parameter could be used to determine the reinforcing-weakening values with a maximum deviation of 5% while not producing insufficient results in the placement (order) of the individual granular material and geosynthetic pairings. This parameter was the area under the function (integral) calculated on the measurement graph of the 40-80 mm shear range, in kN×mm units; it gives correct values only if the reference granular material is the considered railway ballast, the shearing plane is the geosynthetic's plane (i.e., "0-plane"), and the reference qualification parameter is the original recommended parameter from 2012. 20% and 30% were the best relative standard deviations to consider.

The study suggests using parameter #52 (i.e., the area under the shear function [integral] calculated on the measurement graph of the shear range [displacement] 40-80 mm, in kN×mm unit) to evaluate the inner shear resistance of granular materials when the reference granular material is the examined RB. The study discovered potential limitations in replacing the 2012 evaluation option [8] with other parameters, emphasizing the importance of testing the applicability of various methods. The presented results do not imply that a parameter other than #52 cannot be used as a rating value for inner shear resistance, but it should be kept in mind that if a different rating parameter/characteristic is chosen, the results are not comparable with the results from the qualification with #52,

It should be noted that as a partial result, those cases where acceptable results were obtained for each material (RB, CSBCG 0/56, and CGM1) individually could be used subsequently. However, these were not published in this paper because they are of considerable length, and it is challenging to present them systematically. It can be a future research possibility.

Further research with multi-level shear box and larger equipment may help to provide a more complete analysis of geosynthetic reinforced and unreinforced granular materials:

- the application of used railway ballast material (i.e., mainly from crushed stone) that is not exclusively sharp-edged; the use of dry, wet, and oily state materials;
- testing of new and recycled granular mixtures; measurement of different granular mixtures;
- investigation of layer structures on foundations (bases) with different load-bearing capacity values; use of different granular layer thicknesses; use of additional geosynthetics with different characteristics; performing vertical load on the top surface of the above layer; performing dynamic tests;
- application of DEM and/or FEM-DEM considering static and dynamic loads.

Acknowledgement: *This paper was technically supported by the research team entitled "SZE-RAIL". The author would like to thank for the possibility to examine geosynthetic products. The author is very thankful for the English language proofreading by J. Kowalchuk (Széchenyi István University).*

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