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SPECIFIC EVALUATION METHODOLOGY OF RAILWAY BALLAST PARTICLES' DEGRADATION

Purpose. The most railway lines in the world have so called traditional ballasted superstructure. The authors think that it is important to learn about the process of ballast degradation. There are only two types of standardized laboratory test methods in the EU to assess railway ballast particle degradation and describe the rock physic characteristics, but are not suitable for modelling the railway stress-strain circumstances of ballast materials, and they particles. In this paper the authors represent some conclusions from their research that the authors experienced during their individual fatigue laboratory test and from new additional tests. With these kind of testing methods, the deterioration process of railway ballast particles can be assessed more realistic and precisely. **Methodology and new directions.** There are two types of laboratory tests which are presented in this article. The first one was performed by using a shear box with a special layer structure that is loaded by dynamic, pulsating force; while the second one was executed by using a 140 mm diameter HDPE tube with its original closing element that is loaded by ZD-40 machine. **Findings and problems.** There is a development after the R&D work made and published in 2014, in 2017 and 2018 years the ballast particle deterioration process is given according to more intermediate fatigue cycles with individual measurements that show more precise «picture» about the full particle degradation, i.e. breakage process. The authors give more accurate correlation functions between the calculated parameters and load cycles during fatigue. However, there are many factors in the test that need to be improved in the future. Therefore, the authors have discovered other additional tests. **Originality.** The most important goal of the authors that supplement the currently used regulation with new measurement methods. **Practical value** The authors' developed and new methods may serve as a basis for a future instruction or regulation. The publishing of this paper was supported by EFOP 3.6.1-16-2016-00017 project.

Keywords: individual laboratory test method; railway ballast material; particle degradation; breakage; dynamic fatigue test; static pressing test; CT equipment; 3-D image analysis

Purpose

For the railway transport the most widely used superstructure is the ballasted track [23, 24]. The ballast bed bears significant forces and plays important role in load carrying «chain». Each part of the track receives static and dynamic effects in different proportions [1, 2, 50, 52]. The forces and stresses do not transmit consistently in the «sleeper-ballast bed» interface, as well as «grain-grain» connections in the ballast bed. These kinds of effects are the following (without completeness):

– dead weight loading (according to the authors' analysis, it is negligible),

– vehicle forces and effects (on perfect or quite perfect quality track),

– previous geometric and/or structural features on defective track (defects of track geometry, «hammering» of rails at rail joints, defects of welding…etc.) [1, 2, 4, 38, 39, 40, 41, 50, 52],

– natural and environmental effects (freeze, melt, sunshine, rain, wind, flood, etc.),

– effects at turnouts caused be railway vehicles [50, 52],

– effects at level crossing caused by road vehicles,

– effects of tamping machines' hammers during operation,

– other relevant effects (e.g. other vehicle effects, etc.) [0032, 0034].

The degradated ballasted track cause significant geometric changes that cause structural, stability and drainage problems. These problems could shorten the lifetime of the track even in a short term [1, 50, 51, 52].

In nowadays practice it is obvious aspect that required quality ballast [9, 13, 29, 30, 33, 34, 35,

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36, 37, 46, 47, 49] is achievable in requested quantity.

It would be important to embed crushed stone materials with better rock physic properties as railway ballast bed. Using these ballast materials would also facilitate production, transportation, installation, operation and maintenance.

In reality, the previous assumption is not evidence: the employed and developed laboratory testing methods by the authors and the MSZ EN 13450:2003 product standard [37] (in Hungary the Modification 4 in MÁV 102345/1995 PHMSZ [30]) can be suitable for redound and raising with the higher volumes of the LA_{RB} and $M_{DE}RB$.

The developed testing method may be a proposal for the elaboration or modification of new assessment and measurement method and the revision of the values' limits.

There are two types of standardized laboratory test methods in the EU which could describe the rock physic characteristics of the railway ballast and determined in the MSZ EN 13450:2003 product standard [37]:

– Los Angeles abrasion test (MSZ EN 1097-2:2010) [0021],

– Micro-Deval abrasion test (MSZ EN 1097-1:2010) [0020].

These laboratory test methods are not suitable for modelling the railway loads in a real manner with the dynamic force and vibration [0035, 0037], but they can be absolutely useable for satisfy defining the abrasion characteristics of a given aggregate sample and for ensure the checking of the quality level. For the objective judgement of conformability special laboratory breakage test has to be used that consider the more real operation circumstances and stresses.

The unique laboratory test method was developed in 2015 [17], because the standardized tests cannot consider the real breakage and abrasion (i.e. loads from vehicles and other effects). The results of the test were compared with the related regulation of MÁV (Hungarian Railways). The individual laboratory test helps to calculate the required time intervals of ballast screening.

The authors research the theme's extensive international literature. Foreign researchers are actively publishing in the research topic, so there is a comprehensive literature in different areas and different methods: laboratory tests; field tests; DEM and FEM modelling methods and 3D grain shape improvement [6, 14, 15, 22, 31, 32, 42, 43, 48]. Based on this the authors represent the own, individual solution for the unique laboratory test procedure (method) that is able to simulate the stresses more realistic.

The second, additional test is very different from the original one. The authors put ballast particles to a HDPE (water) tube (lined with single layer 1200 g/m^2 geotextile) with its original closing element and loaded by ZD-40 machine static to an ultimate loading value step by step. Before and after each loading stage, ballast sample – with all the particles in the tube – are scanned by a CT (computer tomography) equipment [7, 10, 11, 25, 26]. Because of loading a small aggregate, almost every particle's degradation is trackable.

Hopefully with this new method the authors can achieve breakthrough results, which may serve as a basis for a later standard.

Methodology and new directions

Individual laboratory test

In 2014 a Research & Development project was completed with the finance support of Colas Északkő Ltd.; the public information was published in [17].

In 2017-2018 laboratory test series with improved parameters and modified circumstances were performed [16, 18, 19, 20, 21, 27].

The authors executed the tests with two types of ballast samples because of the different rock mechanic properties (ballast samples from Colas Északkő Ltd.). The samples' basic properties were different from each other (LA_{RB} and $M_{DE}RB$ values). The load cycles were the following: 0.1 million; 0.2 million; 0.5 million; 1 million; 1.5 million, 3 million and 5 million. Every ballast sample should be separate for each fatigue test.

The aspects and detailed parameters of the laboratory test are included in a previous publication [27]. Such parameters which have been taken from the wide literature research are the follows used by the authors to get results:

– F_V (%),
– BBI,
– B_R,
– d<22.4 mm in mass percentage,
– d<0.5 mm in mass percentage,

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– d<0.063 mm in mass percentage,
– d_{60}/d_{10} ratio,
– C_c ratio,
– M ratio,
– λ ratio.

The goal was to effort determine mathematical-physical trends and correlation between characteristics (see above point) and loading cycles of fatigue test.

Application of the CT (X-ray) equipment

While there is a wide range of literature available for the 3-D image analysis, the authors found very little source related to testings of railway ballast and/or civil engineer granular materials with CT equipment. The CT (X-ray) equipment is available to the authors in the laboratory of Audi Hungaria Faculty of Automotive Engineering at Széchenyi István University, Győr (Hungary) [7, 10, 11, 25, 26].

X-rays are a form of energy distribution in the family of electromagnetic vibrations. Computer tomography is a development of traditional X-ray screening technology.

The basic data of the device and some relevant data for one measurement can be read in the authors' previous paper [20].

The numbered and 3-D scanned ballast particles are placed in a 140 mm diameter (inner dimension) HDPE tube (originally a water tube) with its original closing element (see Figure 3) and put it into the CT equipment (digitally technic).

Fig. 3. The HDPE tube with the sample

The measurement method is the following (for the 3-step loading):

– washing, drying and numbering of all the stones,

– measuring the weight of the stones and taking photo of all of them,

– inserting the stones into the HDPE tube (lined with single ,

– placing the HDPE tube into the CT equipment and recording CT 3-D model (initial model),

– loading with ZD-40 machine (until 300 kPa),

– another recording by CT equipment (2nd model),

– loading with ZD-40 machine (until 600 kPa),

– another recording by CT equipment (3rd model),

– loading with ZD-40 machine (until 900 kPa),

– another recording by CT equipment (4th model),

– measuring the particles after the loading (weight, photographing),

– washing and drying the particles,

– measuring the weight and photographing once again.

The one-step loading measurement method is very similar to the previous mentioned one, the authors had to save two recording with the CT equipment (before as well as after loading) and the loading was up to 1800 kPa.

X-ray procedure

Homogeneous beam was emitted through the sample, which diffuses and penetrates (it depends on the material) and as a result of the adsorption, the distribution of the quantum of the x-ray changes and weakens in the image plane, blackens the detector to varying degrees. This creates the x-ray images; that depends on the quality of the ballast material. X-rays can also detect tiny cracks after the loading.

Computer tomography procedure

The object under examination is illuminated with a thin, flat X-ray beam. There is a detector which placed behind the object senses where and how much of the beam has been absorbed along a line. In the same plain, the beam is illuminated from several directions, and a drawing of the details in the plain (slice) is drawn from the measured intensity curves. The plain is then pushed away and rotated again. At the end of the procedure, the spatial structure of the test body can be mapped. «Structure» refers to the arrangement of details that can be distinguished from X-ray transmission capability. Modern CT (X-ray) equipment crawls several slices (up to 1260) at a time, and a test can be performed in a few minutes with the necessary

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calculations. The available CT equipment can be seen in *Figure 4*. *Figure 5* shows an example for measurement.

Basic data of the device, and some relevant data for one measurement:

– A 360° rotation produces 1260 projections (CT-images).

– The number of the lines are 104.

– In case of multi slice: distance between two slices is 210 mm.

– Number of the pixels: 2048 × 2048 (used: 1024 × 1024).

– 2D-pixel size: e.g. 0.19124188 mm.

– 3D-XY-pixel size: e.g. 0.18966927 mm (the edge length of 1 spatial pixel – so called ‘voxel’).

– 3D-Z-pixel size: e.g. 0.1896692 mm.

– X-ray tube: Y.TU 450-D09.

– Tube voltage: 0…450 kV (used 210 kV).

– Current: 2.60 mA (it is related to 210 kV; e.g. 1.213 mA for 450 kV).

– Focus: small.

– Filters:
  - Al: 0.00 mm,
  - Cu: 1.50 mm,
  - Sn: 0.00 mm,
  - Pb: 0.00 mm.
  -

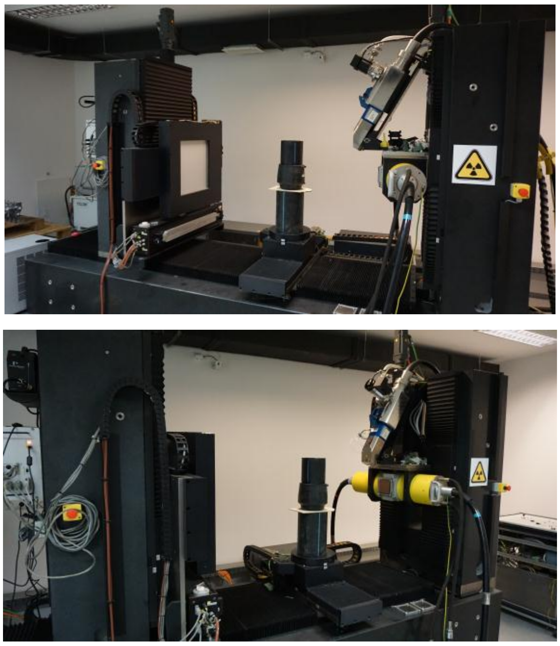

Fig. 4. The CT (X-ray) equipment with the HDPE tube from two viewpoints

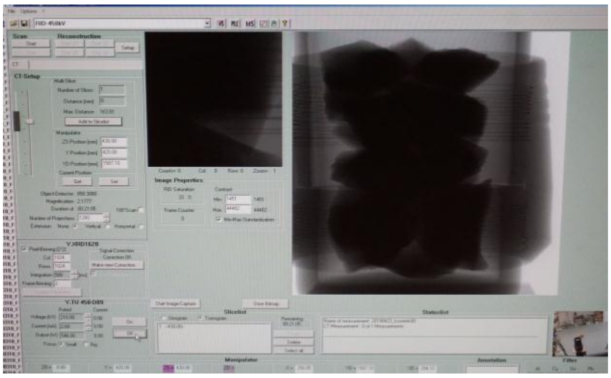

Fig. 5. Preview of a CT measurement, as well as the board of the software

As described above, before and after the loading tests – like the fatigue test – the HDPE tube with the ballast material was scanned by the CT equipment. The authors used CT equipment for the analysis of the breakage. The CT machine’s own software is able to build the spatial frame of the ballast set and the 3-D model could be used in the free software version of GOM 2018 (projection system). The parameters are the following that can be determined by using the 3-D model:

– displacements of the particles,

– volume,

– the set of the particles can be identified.

The weight of the particles after the test was redefined.

After that, the authors performed some loading test with just one-step and the values reached even the 1800 kPa (2000 kPa). The step-by-step loaded and scanned sets can be compared with the software.

Figure 6 and *Figure 7* show some photo from the laboratory measurement.

Fig. 6. Some weighted and numbered particles before loading

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Figure 8 and *Figure 9* show 3-D images (models) made by CT (X-ray) equipment. The samples in the HDPE tube were static loaded with compression stresses of given values (in *Figure 7* from right to left: 0, 300, 600 and 900 kPa; in *Figure 8* from right to left: 0, 1800).

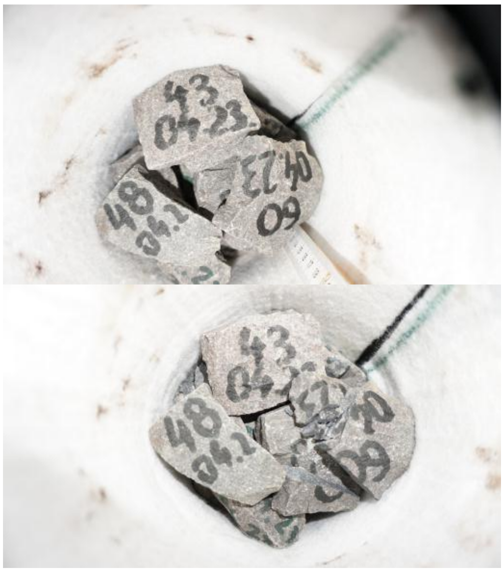

Fig. 7. Numbered particles in the lined HDPE tube before (top) and after (bottom) loading (Test series #3, i.e. maximum compression stress: 1800 kPa)

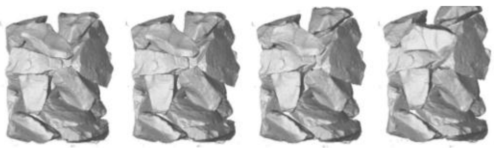

Fig. 8. Recorded 3D images (models) from the loaded aggregates in 3 (4) steps by CT equipment related to test series #2 (from right to left – step #0: before loading, step #1: max. compression stress is 300 kPa, step #2: max. compression stress is 600 kPa, step #3: max. compression stress is 900 kPa)

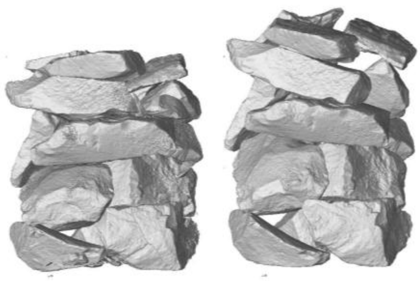

Fig. 9. Recordings from the loaded aggregates in 1 (2) steps related to test series #3 (from right to left – step #0: before loading, step #1: max. compression stress is 1800 kPa)

The authors suppose that the speed of the loading is also a relevant parameter that will be examined in the future.

Findings and problems

In recent papers [16, 17, 18, 19, 20, 21, 27] the relevant correlations were presented in some graphs related to the calculated parameters in case of the individual fatigue laboratory tests.

There is enormous time requirement of this type of testing method, so this is the reason why the authors would like to try to find other measurement methodologies, like the measuring with the CT equipment. It can take 1 to 1.5 month to reach the 5 million cycles in the testing method and the authors used «fresh» ballast material for every measurement (after 100,000, 200,000, 500,000… etc. cycles).

Other problem is the extruded polystyrol layer was significantly deformed during the dynamic test, so in this year the main goal is to evolve the modified layer structure. Changing it for a stiffer and harder layer could help the research in better way.

At the second laboratory tests the evaluation of the results is still ongoing.

The graphs below show the loading curve for the 3-step load and the one-step load (see *Figure 10*. and *Figure 11*.).

The loading curves show that they do not reach the upper limit of the load in a straight line, but they move down in certain places. In these places the ballast particles displacements from each other and breaking. With increasing the load, the fractures in the loading curve are increasingly greater.

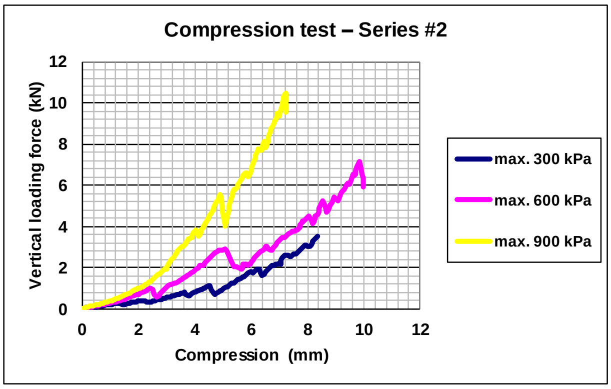

Fig. 10. Loading curves of loadings with max. 300-600-900 kPa compression stress values (3-step loading)

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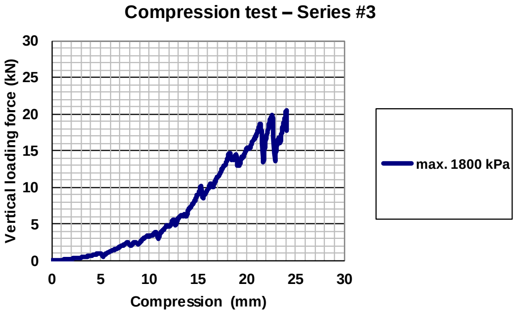

Fig. 11. Loading curve of loading with max. 1800 kPa compression stress value (one-step loading)

The loading curve rises much steeper after every (little) breakpoint.

The preliminary results show the quantity of the «rest» particles from the entire ballast aggregate from the 3-step loading laboratory test (with the HDPE tube). This value calculated from the weight of the original numbered, washed and dried particles without loading and washed and dried particles after the latest loading (it is a percentage value, however it should be taken into account that up to 30% of some stone have broken down). The values can be seen in *Table 1*. The values written with slanted letters show the values that involve the rate of those stones that split into several pieces.

Table 1

The broken particles of the ballast aggregate after 300-600-900 kPa compression stress (the 3-step loading test)

Series number of the tests	The weight of the broken particles [%]
1	0.18%
2	0.14%
3	3.18% (6.26%)
4	1.13%
5	1.06% (3.90%)
6	1.65% (3.64%)

Table 1. shows that none of the samples contains more than 1.7% (with the exception of Series 2#) of the powder of the stone after the latest loading. The percentage of broken stones is also less than 4%, including the number of stones that fell into several larger pieces (not powder, like the previous case).

The authors also investigated that in the tube which particles were broken down mostly of the rows. *Table 2* show the degradation for each rows (ratio of after-loading-weight and before-loading-weight in percentage).

Table 2

The broken particles of the rows at the 3-step loading test

Series number of the tests	Number of the row	The weight of the broken particles [%]
1	1	0.10%
	2	0.06%
	3	0.13%
	4	0.13%
	5	0.47%
2	1	0.00%
	2	0.27%
	3	0.11%
	4	0.09%
	5	0.27%
	6	0.09%
3	1	5.45%
	2	0.62%
	3	1.28%
	4	5.73%
	5	2.80%
4	1	0.15%
	2	1.59%
	3	2.04%
	4	0.57%
	5	1.17%
5	1	0.24%
	2	0.34%
	3	0.67%
	4	0.31%
	5	4.33%
	6	0.21%
6	1	0.51%
	2	0.05%
	3	0.54%
	4	0.35%
	5	6.68%
	6	0.43%
	7	0.91%

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According to the values (with the expection of Series #2) the particles are mostly broken in the lower and middle part (three before the bottom) of the aggregate.

During the test particles in the HDPE tube moved significantly during the test (mainly on top of the aggregate). The authors would like to analyse particle movements in the future.

Originality and practical value

The most important goal of the authors that supplement the currently used regulation with new measurement methods, because the original standardized tests are not loading the samples realistic. The authors' developed and new methods may serve as a basis for a future instruction or regulation.

Conclusions, future scope

The authors would like to reduce the time requirement of newly developed testing methods with improved manner. The authors combine the compression tests with 3-D image analysis (full-field 3-D shape measurement) with the help of CT (X-ray) equipment. The measurement method was developed, the procedure of evaluation methodology is in progress.

Beside them field tests are planned in the Hungarian railway lines. The authors plan to collect samples from old railway lines where ballast aggregates have known PSD (particle size distribution) at the time of construction.

In the laboratory the authors always work in idealized conditions. This is the reason why the particle breakage values are much higher than the values in real circumstances (see measurement results from 2014 and 2017-2018). Besides, the authors could test only one kind of loadings. Tamping machines also break ballast particles during work, so this kind of effect is also needed to be considered in the future research. Delivery of the crushed stone to the site can also be an important parameter that has to be considered.

The authors plan to work with DEM simulations [12, 44, 45], for this a spatial model must be built. The simulations with the laboratory tests would be comparable.

Acknowledgements

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УДОСКОНАЛЕНА МЕТОДИКА ОЦІНКИ РУЙНУВАННЯ ЧАСТОК ЗАЛІЗНИЧНОГО БАЛАСТУ

Мета. Більшість залізничних ліній у світі мають так звану традиційну верхню будову колії з баластним шаром. На думку авторів, для гарантування безпеки руху важливо вивчити процес руйнування баластного шару. У ЄС існує тільки два типи стандартних методів лабораторних випробувань для оцінки ступеня руйнування часток залізничного баластного шару й описання їх фізичних характеристик. Але вони не придатні для моделювання напружено-деформованого стану залізничних баластних матеріалів і їх часток. У цій статті автори представляють методи випробувань, за допомогою яких процес руйнування залізничних часток баласту можна оцінити більш реалістично й точно. Ці методи базуються на висновках із досліджень, індивідуальних лабораторних випробувань на втому, а також із додаткових випробувань. **Методика.** У роботі подано два типи лабораторних випробувань. Перший був виконаний із використанням зсувної коробки зі спеціальною шаруватою структурою, яка навантажена динамічною, пульсуючою силою. Другий тип – із використанням труби з поліетилену високої щільності діаметром 140 мм з оригінальною запірною деталлю, навантаженою машиною ZD–40. **Результати.** Після науково-дослідних розробок, проведених і опублікованих у 2014 році, спостерігається розвиток методів оцінки руйнування баластного шару. У 2017 й 2018 роках під час випробувань руйнування часток баласту було здійснено з більшими проміжними циклами втоми та окремими вимірами, які більш точно показують повне руйнування часток, тобто процес руйнування. Проведено кореляцію між розрахунковими параметрами й циклами навантаження на втому. Однак під час випробування залишається багато факторів, які потребують поліпшення. Тому автори описують інші додаткові тести. **Наукова новизна**. У роботі запропонована вдосконалена методика оцінки руйнування баластного шару залізничної колії, яка дає більш точні результати порівняно з традиційними методами вимірювань.

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Практична значимість. Методи, розроблені авторами можуть служити основою для складання нових інструкцій або правил. Публікація цієї статті була підтримана проектом EFOP 3.6.1-16-2016-00017.

Ключові слова: авторський лабораторний метод випробувань; залізничний баласт; руйнування часток; випробування на динамічну втому; випробування на статичний тиск; КТ-обладнання; аналіз тривимірного зображення

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УСОВЕРШЕНСТВОВАННАЯ МЕТОДИКА ОЦЕНКИ РАЗРУШЕНИЯ ЧАСТИЦ ЖЕЛЕЗНОДОРОЖНОГО БАЛЛАСТА

Цель. Большинство железнодорожных линий в мире имеют так называемое традиционное верхнее строение пути с балластным слоем. По мнению авторов, для обеспечения безопасности движения важно изучить процесс разрушения балластного слоя. В ЕС существует только два типа стандартных методов лабораторных испытаний для оценки степени разрушения частиц железнодорожного балластного слоя и описания физических характеристик горных пород. Но они не пригодны для моделирования напряженно-деформированного состояния железнодорожных балластных материалов и их частиц. В данной статье авторы представляют методы испытаний, с помощью которых процесс разрушения железнодорожных частиц балласта можно оценить более реалистично и точно. Эти методы базируются на выводах из исследований авторов, индивидуальных лабораторных испытаний на усталость, а также из дополнительных испытаний. **Методика.** В работе представлены два типа лабораторных испытаний. Первый был выполнен с использованием сдвиговой коробки со специальной слоистой структурой, которая нагружена динамической, пульсирующей силой. Второй тип – с использованием трубы из полиэтилена высокой плотности диаметром 140 мм с оригинальной запирающей деталью, нагруженной машиной ZD–40. **Результаты.** После научно-исследовательских разработок, проведенных и опубликованных в 2014 году, наблюдается развитие методов оценки разрушения балластного слоя. В 2017 и 2018 годах во время испытаний разрушение балластных частиц было осуществлено с большими промежуточными циклами усталости с отдельными измерениями, которые более точно показывают полное разрушение частиц, т. е. процесс разрушения. Произведена корреляция между расчетными параметрами и циклами нагрузки на усталость. Однако во время испытаний остается много факторов, требующих улучшения. Поэтому авторы описывают другие дополнительные тесты. **Научная новизна.** В работе предложена усовершенствованная методика оценки разрушения балластного слоя железнодорожного пути, которая дает более точные результаты по сравнению с традиционными методами измерений. **Практическая значимость.** Методы, разработанные авторами, могут служить основой для составления новых инструкций или правил. Публикация данной статьи была поддержана проектом EFOP 3.6.1-16-2016-00017.

Ключевые слова: авторский лабораторный метод испытаний; железнодорожный балласт; разрушение частиц; испытание на динамическую усталость; испытание на статическое давление; КТ-оборудование; анализ трехмерного изображения

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