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INVESTIGATION OF INFLUENCE OF THE METAL CORRUGATED PIPE DIAMETER ON ITS STRESS-STRAIN STATE

Josef Luchko[1]; Vitalii Kovalchuk[2]; Ivan Kravets[3]

[1]Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine
[2]Dnipropetrovsk National University of Railway Transport named after academician V. Lazaryan Lviv branch, Lviv, Ukraine
[3]Dnipropetrovsk National University of Railway Transport named after academician V. Lazaryan Lviv branch, Lviv, Ukraine

Summary. *Metal corrugated structures require both high design quality and quality of construction. Significant contribution to the damage initiation and the MCS fracture can be caused by the imperfect methods of calculating MCS in the soil environment and incorrect choice of the structure span, as well as the shape of the structure cross-section.*

The problems of adaptation of foreign standards concerning the design of metal corrugated structures on the railway and motor roads of Ukraine are analyzed, the results of experimental and theoretical calculations of bearing capacity of metal corrugated structures are presented.

It was determined, that the stresses arising in the pipe metal sheets of 1 m till 9 m diameter do not exceed the metal ultimate elasticity of 235 MPa. However, for the 10 m diameter pipe the stresses value exceeds the permissible value of the metal pipe yield strength of 235 MPa.

It is established, that for the pipes of 1 m till 9 m diameter the value of the plastic hinges formation does not exceed the permissible value of 1,0. However, for the 10 m diameter pipe the value of the plastic hinge formation ratio is 1,531, which is unacceptable for this steel grade. Since in the 10 m diameter pipe due to the load from the locomotive 2M62 the plastic deformations are formed in the metal pipe, it can cause the destruction of the transport structure as a result.

Key words: *metal corrugated structure, structure diameter, stress-strain state, plastic hinge, railways rolling stock.*

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Introduction. Metal corrugated structures (MCS) have been applied for the construction of water pipelines other buried pipelines since the late XIX century [1 – 7].

Nowadays great experience in the operation of metal corrugated pipes, being buried under the railways and motor roads, was obtained in the world. During their long-term operation these structures have been observed and tested for many times and as the result their operation economy, durability and reliability were determined, as well as the problems of operation in the soil environment of the railway and motor roads were revealed [8 – 9].

The corrugated pipes have been widely applied in Europe only for the last 50 years [10 – 12]. Nowadays among the famous world companies are the Italian company FRACASSO (*152 x 51 mm*, the pipe wall thickness being *3 – 7 mm*) [13], the Norway-Sweden-Finland company VIACON (*150 x 50 mm*, the pipe wall thickness being *3 – 7 mm*). They provide the need in metal corrugated structures for the countries of Europe, America, Africa and Australia. In Poland, Sweden, Italy, USA and Canada (Canadian company ARMTEC) [12] the application of MCS is being developed dynamically nowadays.

One of the most famous companies dealing with the design, production and sale of the corrugated steel structures in Ukraine is the company ViaCon [14], which was set up in 1986 in Sweden and Norway. Today ViaCon group comprises more than 30 affiliations in

 Corresponding author: Vitalii Kovalchuk; e-mail: kovalchuk.diit@gmail.com

18 countries of Europe and Middle East. It produces corrugated metal structures, which are applied for the construction of bridges, roads, transport tunnels, stock-yards, pedestrian and biological passages and water pipelines. The company ViaCon-Ukraine applies the MultiPlate, SuperCor and HelCor structures for metal corrugated structures in the transport structures.

Investigations relevance. The experience in MCS maintenance and operation testifies, that nowadays, in fact, their technical operation life, which must meet the requirements as to the design durability of artificial structures on the motor roads, under which they are buried, is not provided. It needs regular monitoring and estimation of their structural health, prediction of their bearing capacity change, estimation of the residual operating life, development of measures for providing the necessary durability, which generally contributes to high value of their maintenance and operation.

Experience in the MCS application in the soil environment conclusively proved, that the structures in question, possessing advantageous properties, are specified by the relatively low reliability and durability. During their operation the growth of unacceptable deformations is observed in many cases, the increase of horizontal and decrease of vertical pipe diameters in particular. To exclude the unacceptable pipe deformations it is necessary to develop the methods of the MCS calculations being in operation together with the filling soil, which will make possible to predict the MCS strength and durability. These problems have been paid much attention to by the researchers since the first application of MCS in construction. But the investigations of the effect of the pipe diameter value on the stress-strain state of the structure is still of great importance nowadays. Properly chosen values of the pipe cross-section sizes will provide both the structure durability and the hydrological and hydro-dynamic safety of MCS.

The objective of the paper is to carry out investigations of the pipe diameter value effect of the metal corrugated structure on its stress-strain state and to check the conditions of the plastic hinge formation in the metal pipe. Here the investigations were performed under the constant thickness of the metal corrugated pipe and parameters of the dynamic loading and the soil fill.

Analysis of the available investigations and publications. While designing the metal corrugated structures the designers faced some problems. Thus, the foreign [7, 9, 15 – 17] and national [18] standards being compared, sufficient differences in the boundary fill heights above the metal corrugated pipe have been revealed at equal thickness of the corrugated wall. The foreign pipes bearing strength appeared to be much higher for the sufficiently higher fills. It caused the appearance of new problems in mastering new shapes and sizes of the MCS pipe diameters.

Initially it was assumed, that the difference in the MCS bearing strength is caused by the differences in the physical-mechanical properties of the pipe metal. But the study of foreign standards testified, that the grades of national steels being used for the MCS construction, are much more stronger than those foreign ones. The real reason was that of principle differences of rates in the MCS calculations. In Ukraine the calculation of the water pipes of up to *3 m* diameter is performed according to the standards [18].

Due to it the first boundary state is determined by the boundary static equilibrium of interrelation of the system «structure-soil» and, being based on it, it is possible to find the bearing strength of the pipe. The presented formula contains some empiric coefficients and does not include real strength characteristics of the pipe metal and the parameters of the soil fill. But this condition itself in most cases is the limiting one. In foreign standards [7, 9, 15 – 17] the strength and stability of the corrugated pipe wall is estimated due to its effect on the pipe vault of the soil weight and pressure, caused by the temporary loading on the pipe upper level. Mutual work of the MCS and soil under sufficient fill height above the vault is taken into account by lowering the rate to the amount of temporary and constant loadings, which depend on the level of soil stabilization round the structure. Similar strength and stability check of the pipe wall are included in the standards of Russia [15], but it is almost never limiting. Thus, the pipe calculation due to the boundary static equilibrium of the interrelation of the system «structure-soil» is the problem itself, which restricts the area of the structures application.

The pressure caused by the temporary loading is found differently. Under the equal fill height above the pipe the portion of the temporary loading in the total pressure at the pipe vault, as a rule, according to the Ukrainian standards [7, 9, 15 – 17] dynamics is taken into account. Under the minimum fill the intensity according to the foreign standards of loading is greater than that similar one according to the national standards.

The studied scientific-research papers do not investigate the effect of the pipe diameter size on the stress-strain state of the structure. Its specific feature is the constant value of the structure fill, starting from the railway sleeper foot or the motor road paving asphalt foot to the pipe vault.

The developers of typical structures are not capable enough to make decisions. Their developments must be based on the well-known approved theories, moreover, the engineer's decisions must be fostered by some recommendations. Thus, the ideal decision to foster the construction of metal corrugated structures would be, if there were some recommendations (guidelines) as to the design and estimation of the bearing strength of metal corrugated structures being buried under the railway gauge.

Method of investigation of the MCS stress-strain state. The bearing strength of the metal corrugated pipe is tested from the point of view of the normal force, as well as the combination of the normal force and the bending moment. Here the maximum stresses initiated in the metal pipe walls are calculated due to the Navier's equation

$$\sigma = \frac{N_{d.s}}{A} + \frac{M_{d.s}}{W} < f_{yd}\,, \tag{1}$$

where $N_{d.s}$, $M_{d.s}$ – forces and force moments under normal operation; A – cross-section area and the moment of cross-section pressure on the pipe length unit; f_{yd} – the pipe steel ultimate yield; W – the moment of the pipe length unit pressure.

Taking into account the fact, that the metal pipe is corrugated and the investigations of the stress-strain state of the pipe will be under different diameters, let us analyze the method of determination of the normal forces and bending moment being initiated in the metal pipe.

Determination of normal forces on the MCS. Normal forces in the pipe walls are calculated according to the recommendations [19] due to the dependencies:

$$\begin{gathered} h_{c.red} / D \le 0.25; \\ N_t = p_{traffik} + (D/2)q, \end{gathered} \tag{2}$$

$$\begin{gathered} 0.25 < h_{c.red} / D \le 0.75; \\ N_t = (1.25 - h_{c.red} / D)\, p_{traffik} + (D/2)q, \end{gathered} \tag{3}$$

$$0.75 < h_{c.red} / D;\;\; N_t = 0.5 p_{traffik} + (D/2)q\,, \tag{4}$$

where q – distributed loading caused by the rolling stock; D – pipe diameter; $h_{c.red}$ – value of the soil fill.

Normal force caused by the soil environment is found due to the formula

$$N_j = 0{,}2\frac{H}{D}\rho_1 D^2 + S_{ar}\left(0{,}9\frac{h_{c.red}}{D} - 0{,}5\frac{h_{c.red}}{D}\frac{H}{D}\right)\rho_{cv} D^2, \qquad (5)$$

where ρ_1 – average specific weight of the fill material (till the pipe vault); ρ_{cv} – average specific weight of the fill material (above the pipe vault till the fill height h_c).

Coefficient S_{ar} takes into account the arc effect of the soil distribution in soil above the water pipeline, which is initiated at great height of the fill and is calculated due to the dependencies:

$$S_{ar} = \frac{1-e^{-\kappa}}{\kappa},$$
$$\kappa = 2S_v\frac{h_c}{D}, \qquad (6)$$
$$S_v = \frac{0{,}8\tan\varphi_{cv.d}}{\left(\sqrt{1+\tan^2\varphi_{cv.d}} + 0{,}45\tan\varphi_{cv.d}\right)^2},$$

where $\varphi_{cv.d}$ – project angle of the soil internal friction for the metal part of the pipe due to the formula, taking into account the parameters of the fill soil γ_n, γ_m and the natural angle of the soil internal friction

$$\tan\varphi_{cv.d} = \frac{\tan\varphi_{cv.k}}{\gamma_n\gamma_m}. \qquad (7)$$

In the formula (7) the value of γ_m, as a rule, equals *1,3*. The angle of internal friction, being used in the formula, is that of the soil above the pipe vault. The project normal forces during normal operation are found due to the formula

$$N_{d.s} = (\psi\gamma)_{j.s}\cdot N_j + (\psi\gamma)_{t.s}\cdot N_t; \qquad (8)$$

in the boundary possible state

$$N_{d.u} = (\psi\gamma)_{j.u}\cdot N_j + (\psi\gamma)_{t.u}\cdot N_t, \qquad (9)$$

in the state of long-term fatigue loadings

$$N_{d.f} = (\psi\gamma)_{t.f}\cdot N_t, \qquad (10)$$

where $\psi\gamma_{j.s}$, $\psi\gamma_{j.u}$, $\psi\gamma_{t.f}$ – coefficients of safety chosen according to the recommendations [19] for certain boundary states.

Determination of bending moments for MCS. The bending moment in the pipe wall depends on the interrelation between the soil and pipe rigidity. This relation is signed as λ_f and is found due to the formula

$$\lambda_f = E_{jd}\cdot D^3/(EI)_s, \qquad (11)$$

where E_{jd} – shearing modulus for soil; $(EI)_s$ – pipe bending rigidity.

The bending moment in the pipe caused by the surrounding soil and the soil loading in the working capacity boundary state is found due to the formula

$$M_j / \rho_1 D^3 = -f_1 f_3 f_{2,surr} + S_{ar} \frac{\rho_{cv}}{\rho_1} \frac{h_c}{D} \left(\frac{R_t}{R_s} \right)^{0.75} f_1 f_{2,cover} , \tag{12}$$

where f_1, $f_{2,surr}$, $f_{2,cover}$, f_3 – coefficients calculated depending on the geometric and physical properties of the soil fill [19].

The equation (12) is based on the experimental observations [19]: when at the reverse fill the stabilization occurs round the pipe plastic structure, it is pressed inside along the sides and in the pipe vault the negative bending moment is initiated. This moment is maximum, when the level of fill reaches the level of the pipe top, which is presented by the first summand in the right part of the equation (12). When the filling goes further, above the level of the pipe top, the pipe structure is stressed down and the negative moment decreases. If the fill height is good enough, the sign in the pipe top can be changed in this time and becomes positive.

The project bending moments in the pipe caused by the soil and the rolling stock are of different directions in different points of the cross-section. That is why to determine the maximum option of the loading superposition the check must be performed in accordance with the following formulas. The project moments of forces in the state of normal operation are found due to the formula

$$M_{d.s} = M_{jd.s} + M_{td.s} . \tag{13}$$

The project moments of forces for the rolling stock loading in the boundary possible state are found due to the formula

$$\left. \begin{aligned} M_{td.s}^{max} &= \left(\psi\gamma\right)_{t.s}^{max} \cdot M_t \\ M_{td.s}^{min} &= \left(\psi\gamma\right)_{t.s}^{min} \cdot \left(-M_t / 2\right) \end{aligned} \right\} . \tag{14}$$

In the boundary possible state the project moments are calculated due to the formula

$$M_{d.u} = M_{jd.s} + M_{td.u} . \tag{15}$$

At the state of long-term fatigue loadings the moments range is calculated due to the formula

$$M_{d.f} = \left(\psi\gamma\right)_{t.f} \cdot M_t \cdot 1.5 . \tag{16}$$

The check of the plastic hinge development in the pipe top at the boundary state will be performed under the maximum loaded part of the pipe according to the method [19] due to the formula

$$\alpha = \left(\frac{N_{d.u}}{\omega f_{yd} A} \right) + \left(\frac{M_{d.u}}{M_u} \right) \le 1.0 , \tag{17}$$

where $N_{d.u}$, $M_{d.u}$ – forces and force moments in the state of normal operation; *A* – cross-section area and the cross-section pressure moment on the unit of the pipe length; M_u – acceptable value of the bending moment for the unit of the pipe profile, under which the yield stresses are obtained.

Basing on this method the estimation of the MCS stress-strain state was performed depending on the metal pipe diameter. With this purpose the structure Multiplate MP 150 is being analyzed as the round cross-section (Fig. 1).

The corrugated wave length is *150 mm*, its height is *50 mm*, the thickness of zink coating is *85 micr* $(567\ g/m^2)$. The amount of fill above the metal corrugated pipe top is *1,88 m* at the fill soil deformation modulus *33 MPa* and under the specific weight of the fill soil $\gamma = 20\ kH/m^3$. Modulus of elasticity of the pipe steel is $E = 2,1 \cdot 10^5\ MPa$ and the Poisson's rate of the structure metal is $\nu = 0,25$.

The loadings on the structure were caused by the railway rolling stock. The maximum equivalent forces initiated from the locomotive 2M62 are obtained in the paper [20].

To obtain the stress values and to check the conditions of the plastic hinge formation in the metal pipe vault, depending on the diameter, the software was developed using the licensed mathematic package Mathcad 14.

The investigations of the stress-strain state of the structure was performed on the *1 m* till *10 m* diameter pipe. The fill height was constant above the pipe $h_c = 1,88\ m$.

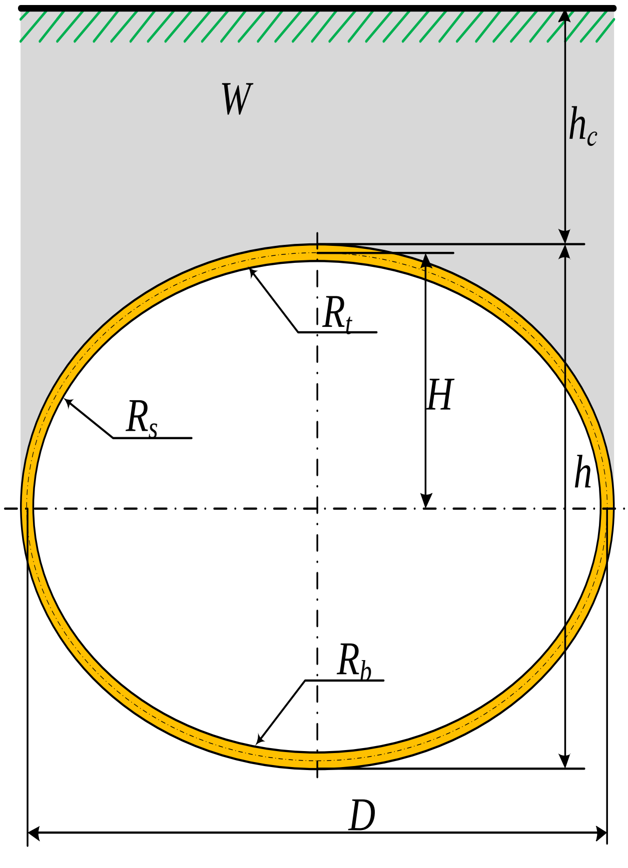

Figure 1. Geometric characteristics of the investigated metal corrugated structure

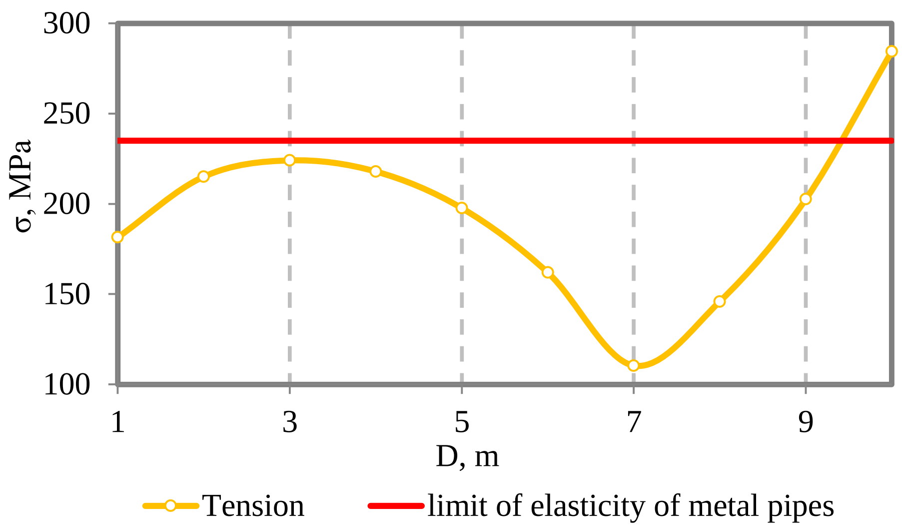

Figure 2. Dependence of the stress-strain state of the metal corrugated pipe on the structure diameter

As it is seen in Fig. 2, the stress values initiated in the pipe metal at the pipe diameter *1 m* – is *181,4 MPa*, *2 m – 215,03 MPa*, *3 m – 224,05 MPa*, *4 m – 217,9 MPa*, *5 m – 197,6 MPa*, *6 m – 161,94 MPa*, *7 m – 110,4 MPa*, *8 m – 145,84 MPa*, *9 m – 202,5 MPa*, *10 m – 284,3 MPa*. Thus, at the pipe diameters from *1 m* till *9 m* the stresses initiated in the pipe metal sheets do not exceed the metal ultimate yield *235 MPa*. But at the pipe diameter *10 m* the stress values exceed the permissible value of the ultimate yield of the metal pipe *235 MPa*.

The results of checking the conditions of the plastic hinge formation at the top of the metal corrugated pipe, depending of the structure diameter, are presented in Fig. 3.

As it is seen in Fig. 3, the value of the plastic hinge initiated in the pipe metal at the pipe diameter *1 m* is *0,727*, *2 m – 0,869*, *3 m – 0,905*, *4 m – 0,863*, *5 m – 0,801*, *6 m – 0,673*, *7 m – 0,449*, *8 m – 0,473*, *9 m – 0,950* and *10 m – 1,531*. Thus, at the pipe diameters from *1 m* till *9 m* the value of the plastic hinge formation does not exceed the permissible value *1,0*. But at the pipe diameter *10 m* the coefficient value of the plastic hinge formation is *1,531*, which is not permissible for the given grade of steel. As at the pipe diameter *10 m* the plastic deformations caused by the locomotive 2M62 loading, will be initiated in the pipe metal, it will result in the damage of the motor road structure.

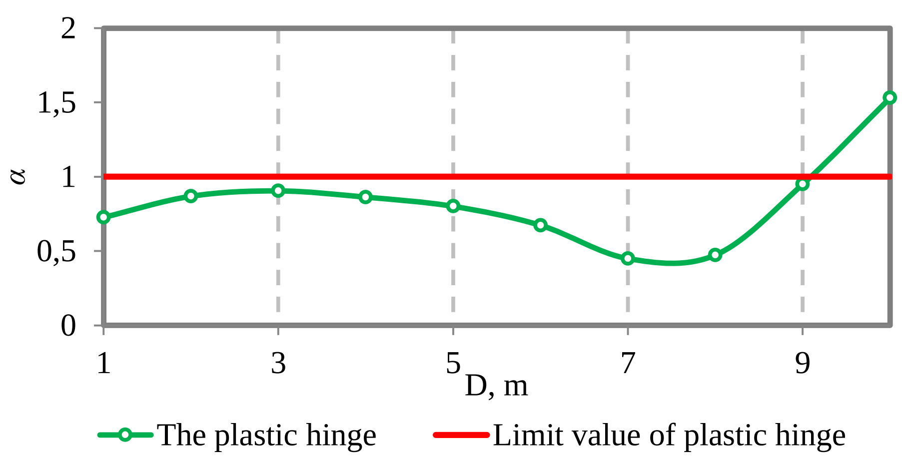

Figure 3. Dependence of the plastic hinge formation at the top of a metal corrugated pipe vault depending on the structure diameter

While constructing the transporting structures, using the metal corrugated structure with the round cross-section, it is recommended to use metal pipes of the *1 m* till *9 m* diameter as those being able to provide the operation reliability according to the criterion of the permissible stresses initiation and formation of the plastic hinge in the pipe metal.

Conclusions and research prospects. The developed method makes it possible to conduct research of the pipe diameter effect on the MCS stress-strain state and the value of the plastic joint formation in the vault of the metal pipe. When constructing transport structures, using the metal corrugated structures of a circular cross-section, it is recommended to build structures with a metal pipe of the diameter from *1 m* to *9 m*, which provide reliability of operation according to the criterion of permissible stresses initiation and plastic hinge formation in the metal pipe. The application of metal corrugated structures of *10 m* diameter and more with the round cross-section on the railways of Ukraine is not permissible, because a plastic joint formation in the MCS metal is possible.

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ВПЛИВ ВЕЛИЧИНИ ДІАМЕТРА МЕТАЛЕВОЇ ГОФРОВАНОЇ ТРУБИ НА ЇЇ НАПРУЖЕНО-ДЕФОРМОВАНИЙ СТАН

Йосип Лучко[1]; Віталій Ковальчук[2]; Іван Кравець[3]

[1]Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна
[2]Дніпропетровський національний університет залізничного транспорту імені академіка В. Лазаряна, Львівська філія, Львів, Україна
[3]Дніпропетровський національний університет залізничного транспорту імені академіка В. Лазаряна, Львівська філія, Львів, Україна

Резюме. *Встановлено, що металеві гофровані конструкції дуже вимогливі як до якості проектування, так і до якості будівництва. Вагомий внесок у появу пошкоджень та руйнувань МГК може спричинити недосконалість методик розрахунку МГК у грунтовому середовищі та правильність вибору прольоту споруди і форми поперечного перетину конструкції.*

Проаналізовано проблеми адаптації закордонних нормативних документів щодо проектування металевих гофрованих конструкцій на залізничних та автомобільних дорогах України.

Встановлено, при діаметрах труб від 1 до 9 м напруження, які виникають у металевих листах труби, не перевищують межу пружності металу 235 МПа. Проте при діаметрі труби 10 м величина напружень перевищує допустиме значення межі текучості металевої труби 235 МПа.

Встановлено, що при діаметрах труб від 1 до 9 м величина утворення пластичного шарніра не перевищує допустимої величини 1,0. Проте при діаметрі труби 10 м величина коефіцієнта утворення пластичного шарніра складає 1,531, що є недопустимим для даної марки сталі. Оскільки при діаметрі труби 10 м внаслідок навантаження від локомотива 2М62 утворяться пластичні деформації у металі труби, відповідно це може призвести до руйнування транспортної споруди.

Ключові слова: *металева гофрована конструкція, діаметр споруди, напружено-деформований стан, пластичний шарнір, рухомий склад залізниць.*

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