Full-Scale Seismic Testing of Large-Span Embedded Steel Corrugated Structures

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SUMMARY
Application of large-span steel corrugated structures (LSCS) as linings for transportation systems, water intakes and other systems has been increasing. The spans of structures amount to 10-12 m and more. With due regard to their importance the increased requirements to their reliability and good conditions under earthquake are placed on transportation systems and LSCSs.
Analysis of earthquake effects on the LSCS had shown that a part of large-span structures had been damaged. This is so because the dynamic response of the ground had been underestimated when designing the structure. To evaluate the errors introduced and to design seismic isolated LSCS we need to compare the calculation results with the data of site observation or with the results of large-scale dynamic testing. Under the conditions of deficiency of the site observation data a specific importance is assigned to the results to be received during experiments with LSCS full-scale models.
In Russia such tests have been conducted on the ground seismic platforms with a combined drive (explosive and mechanical). As a LSCS full-scale model we use a semi-circular 7-meter-span arch, which is made from 5-mm-thick metal sheet with a 381*140 mm lobe produced by Gidromontazh Company (Russia).
During the course of tests the seismic vibrations of soil and the LSCS model in question have been tested for vertical and horizontal directions under one and two-component motions of the seiamic platform. Thus the seismic stability of this full-scale object had been tested directly in accordance with similarity laws. Such testing practices made it possible to reproduce the real conditions of LSCS installation, variation of LSCS-soil system parameters, LSCS efficiency check, including bolt fastenings, at sequential rise of simulated earthquake loading up to the destruction moment. Thus, for the first time we had acquired the detailed information for comparing the calculation results being received on the basis of various programs for the models, which correspond to testing conditions and measurement results for deformations, stresses and deflections.

Keywords: embedded corrugated structures steel, full-scale testing, seismic platform

1. INTRODUCTION

Steel corrugated structures are bolt-fastened in trenches from annular and segmented prefabricated elements, then they are filled with soil which characteristics had been predetermined. Filling was done with layer-by-layer soil packing. Selection of filling type and erection mode should ensure composite action of “LSCS – soil” flexible system under static and dynamic loading. In contrast to traditional flexible concrete linings the LSCS design allowed for development of large deformations, including plastic ones, under extreme loads in LSCS and surrounding soil. At present in Russia and abroad there is experience in building various LSCS constructions, which differ in their cross sections (circle, ellipse, arch, tunnel etc) and overall dimensions.

The forces, to act on the embedded LSCS depend on a number of factors, such as structure geometry, redistribution of shallow and concentrated loads in the filled soil, LSCS material properties and surrounding soil characteristics. When designing a LSCS usually three types of loading are considered: dead, live and seismic. Dead loads are controlled by pressure of LSCS surrounding soil. Live loads, most often, are caused by traffic flow along the road embankment or inside the LSCS.

Concentrated-load stresses from wheel pairs in the soil form additional-to-static pressure on the LSCS.

The processes of soil pressure formation and the laws of dynamic deformation for the “LSCS – soil” system are complicated noticeably under seismic input. Joint vibrations of the structure are of substantially non-stationary nature, under high-power intensive loading occurrence of plastic zones and irreversible deformations would be possible. In spite of this up to now the main requirement to LSCS seismic stability was limited to the requirement on the absence of the filled soil dilution. Observation data indicate the need for more sophisticated analysis of seismic loading features when designing large-span LSCSs.

As a whole the LSCS design evaluation confirms the power of the engineering solution proposed for corrugated steel arch to withstand static and seismic loading reliably under conservative approach for setting the acting loads.

Design seismic analysis has been carried out with the use of a priori assumptions on the conditions of LSCS-soil contact. It should be noted that soil model selection, wording of contact conditions, including the contact between soil layers, between the LSCS foundations and sub-soil could bear strong influence on the calculation results. This is why a detailed validation, including experimental one, is necessary.

Plenty of data to be used for designing and seismic analysis can be received at full-scale and large-scale testing on seismic platforms.

2. EXPERIMENTAL SEISMIC ANALYSIS OF LSCS

Important feature of LSCS is interrelation of response of the steel corrugated structure and the soil under static and dynamic loading. As a consequence, the object of experimental investigations could be a model of the system, for which inclusion of the LSCS-simulating structure and a fragment of its surroundings, which characteristics are adequate to soil properties, is mandatory. The main method of experimental investigation for such interconnected system is scale modeling.

Regularities of joint system vibrations under earthquake are complicated markedly due to non-stationary nature of loading, opportunity of formation of plastic flow zones, irreversible deformations. The most dangerous is manifestation of these effects in the contact area between the shell and soil back filling, they can result in undesired disturbance of system deformation compatibility. In case of applying deep-corrugation plates the contact area size increases substantially, soil pressure distribution can be substantially nonuniform on the wavy LSCS surface. As a consequence, seismic design assumption that small-sized corrugation smoothes the LSCS shell and averages the soil reaction on the contact can appear too rough. Objective evaluation of the effects expected can be received during large-scale physical experiments. Since existing test benches give no way to conduct seismic testis of the LSCS projected in scale (LSCS diameter ~ 10 m, height ~ 5 m), the object for physical experiments shall be a model of the system, necessarily including steel structure which simulates deep-corrugated LSCS and a back-filling fragment the characteristics of which correspond the properties of the soil back filling at the construction site. The primary complexity in organization of bench model seismic tests is in necessity to satisfy simultaneously the similarity conditions of the soil physically nonlinear properties, the geometrical and rigidity characteristics of the compound corrugated steel shell and conditions of its fixing on foundations, the initial stressed-deformed state and dynamic wave pattern of non-stationary seismic loading.

Good potential for accumulation of experimental data on dynamic system reaction is presented by large-scale seismic platform testing on special seismic platforms. The method for seismic platform tests for LSCS analysis and, consequently, selection of a particular testing machine is based on meeting a number of requirements.

Organization of experiments with nonlinear structure models is based most often on the theory of extended similarity of solid deformable bodies. It should be noted, that this theory is addressed when studying the stressed-deformed state of "soil – foundation – building construction" system and does not include rather rigorous requirement on linearity for the system characteristics. According to this theory there is a possibility for testing without special additional loads, compensating gravity action at equality of accelerations of the prototype W_H and its model W_M.

Relations of simulation conditions are as follows: for dimensions – $l_M = \alpha\, l_H$, for stresses – $\sigma_M = \beta \sigma_H$,, for relative deformations – $\varepsilon_M = \gamma\, \varepsilon_H$, for density of material – $\rho_M = \delta\, \rho_H$, for angles of rotation – $\varphi_M = \gamma \varphi_H$, for deflections – $\zeta_M = \alpha\, \gamma \zeta_H$, for concentrated forces – $P_M = \alpha^2\ \beta\ P_H$, for concentrated moments– $M_M = \alpha^3\ \beta\ M_H$, for stiffness – $B_M = \dfrac{\alpha^4 \beta}{\gamma} B_H$, for stress-strain modulus – $E_M = \dfrac{\beta}{\gamma} E_H$, for velocity of seismic waves – $C_M = \sqrt{\dfrac{\alpha}{\gamma}}\, C_H$, for displacement – $u_M = \alpha\ \gamma\ u_H$, for speed – $\upsilon_M = \sqrt{\alpha \gamma}\ \upsilon_H$, for time – $t_M = \xi\ t_H$, where $\beta = \alpha\, \delta$, $\xi = \sqrt{\alpha \gamma}$, and indices «M» and «H» relate to the model and the prototype, respectively.

Adherence of similitude parameter can be provided due to special selection of low-modulus materials when the models are manufactured and due to realization of appropriate parameters of seismic platform motions. It is necessary to note that similarity of relation between the stress and deformation of the prototype and the model materials should be applied to the whole process, including plastic regions and state of unloading. Specific problems arise when selecting the modeling material mechanical characteristics of which should be the same with soil.

It is to be noted that properties of various soil types differ substantially under conditions of static and dynamic loading. Description of plasticity properties is usually done in the form of von Mises-Schleicher plasticity condition, use of which is made in the ANSYS program package. The most important is the influence of surrounding-soil strength on the shear. Under dynamic loads a considerable reduction of soil-shear resistance and as a consequence a decrease of soil pressure can take place. Finally these processes to a considerable extent can govern LSCS good condition at earthquake loading.

These characteristics of static and dynamic soil deformation with due regard to importance of correct evaluation of contact conditions and pressure change laws under seismic input practically confirm the wisdom of testing the real soil, located near the LSCS with design technology observance. Thus, for the soil we have $\delta = 1$. In addition it will be noted, that value γ at large deformation should be equal to 1. If the LSCS model had been manufactured from the same metal, as under full-scale conditions, the identity of relations between stresses and deformation for model and prototype ($\gamma = \beta = \zeta = 1$) was ensured. The thickness of LSCS can be chosen from $\sigma_{SM} F_M = \alpha^2 \beta\ \sigma_{SH}\ F_H$, where σ_S – yield limit, F – area of section $F_M = \alpha^2\ F_H$.

Application of natural materials in model conditions limits the possibility to reduce the model dimension. Value of coefficient α can in this case alter within the range from 1 to 1/6. This situation together with necessity to reproduce the required distance between LSCS and reflecting boundaries determines linear dimensions of the LSCS model. According the design evaluations the zone of influence of soil-filled area boundaries makes up 1.0÷1.5 from the LSCS span. As a consequence, the mass of the object tested including the masses of LSCS, soil and edging, exceeds 50 t.

Thus, large-scale tests of large-span LSCS model for seismic input can be conducted on large seismic platforms. Moreover, only multi-component seismic platforms with controlled drive may be used, as only non-stationary alternating loading of both soil and LSCS answers the conditions of exact reproduction of earthquake effect.

From the load-carrying capacity of these seismic platforms a linear scale α of modeling for LSCS and adjoining soil section is 1:1.5÷1:4. In this case with the use of natural materials the modeling may be based on criteria of simple similarity: for dimensions – $x_M = \alpha x_H$, $y_M = \alpha y_H$, $z_M = \alpha z_H$; for stresses – $\sigma_M = \sigma_H$; for relative deformations – $\varepsilon_M = \varepsilon_H$; for density of materials– $\rho_M = \rho_H$; for mass – $m_M = \alpha^3 \ m_H$; for stress-strain modulus – $E_M = E_H$; for time – $t_M = \alpha \ t_H$.

As noted earlier, the wave effects of seismic input can appear important at LSCS loading in longitudinal direction. If ignore these effects when studying the response of structure cross section we assume, that rigid chamber walls simulate the surfaces of compact rock, which in real conditions contact with the filled soil, and commit motions according to the preset law together with seismic platforms. Motion of the platform with the test model on it can be one-cpmponent (vertical, horizontal) or two-component. In conditions of observing the simple similarity for each component the parameters of seismic platform motion shall satisfy the relations: for accelerations – $W_M = \frac{1}{\alpha} W_H$; for speeds – $\vartheta_M = \vartheta_H$; for displacements – $u_M = \alpha \ u_H$; for time response – $\tau_M = \alpha \ \tau_H$.

Preliminary analysis had shown that large-scale seismic tests of a back-filled arched gallery structure made from LSCS with deep-corrugated plates can be conducted on the seismic platform. During the period from 2001 on this seismic platform we had performed seismic stability prove-out for several objects located in ground (water) medium or in contact with it.

Seismic platform is a rectangular steel structure 11,3*5,0*0,5 m, placed open inside the rigid box-type framing on pneumatic pillow-type elements. On the seismic platform a tray with rigid walls is fixed. Dimensions of the internal tray cavity are 9,5*2,6*4,0 m. The testing machine is located in the open site.

For provision of seismic platform motion required according to test specifications there is used a hydraulic actuator which consists of powder tappet set, pneumatic and hydraulic actuators, with the aid of which pulse loading is realized, vibration machine for vibration loading reproduction and a system of their operation program control. Due to superposition of these processes and their superimposing on the resiliently supported seismic platform vibrations a test load input with preset parameters is formed. Seismic platform can travel both in unidirectional-type (horizontally, vertically) and in multicomponent-type, including rotational components.

Controlling the test motion parameters apart from programmed engagement of the hydraulic actuator devices is produced by variation of powder pusher characteristics (mass, blasting charge type), pneumatic and pneumohydraulic actuators (pressure value, throttle resistance, filling level etc), vibration machine location and operation modes. As a result of task-oriented selection of hydraulic actuator characteristics the seismic platform ensures realization of three main types of seismic tests:
- "seismic shock" tests, reproducing shaking the embedded structures under close industrial explosions, for example;
- "rigid seismic" tests, simulating, among the other things, seismic vibration on high marks of buildings and structures (12 m and higher), and reproducing in accordance with similarity laws the conditions of seismic tests of embedded structures small-scale models;
- "soft seismic" tests, simulating motions of the soil and the full-scale or large-scale examples of embedded structures under various intensity earthquakes.

Dynamic range of amplitude-time values of the seismic platform motions at these test types are presented in Table 1.

Table 1. Parameters of test conditions

Type of loading condition	**Axial accelerations (g)**		**Axial speeds (m/s)**		**Axial displacements (m)**		*Duration of loading, s*
	oz	**ox (oy)**	**oz**	**ox (oy)**	**oz**	**ox (oy)**	
Seismic shock	+15/-2	±30	+3/-1	±3	+0,1	±0,1	up to 1, 0
Rigid seismic	±7/-2	±10	±2	±2	±0,2	±0,2	up to 10, 0
Soft seismic	±2	±2	±1	±1	+0,3/-0,2	±0,5	up to 60, 0

Seismic tests statement for a back-filled gallery model assumes for using "soft seismic" loading. In this case application of powder pushers is not needed. In preparation for testing the parameters of other hydraulic actuator elements are established due to the condition of required reproducing the seismic input up to 9 as per the MSK-64 scale, representative for Sochi region (Russia). The tests object is a semi-circular arch, made from deep-corrugated plates 381*140 mm produced by Gidromontazh Company. The arch diameter along the axis is 5,0 m, its height is 2,55 m, corrugated plate thickness is 4 mm. Linear dimensions of the arch tested to scale 1:2 corresponds the full-scale structure, designed for installation in the back-filled gallery. Supporting arch elements are fixed symmetrically on the internal cavity base of the seismic platform tray relative to its vertical walls in the test loading plane. The arch width is 2,6 m and is equal to the seismic platform tray width. Internal tray cavity around the arch is filled with compacted sand-gravel mixes. Back-filling height above the arch vault is 0,7 m. Figure 1 shows a back-filled gallery fragment with a semi-circular arch made from LSCS in the seismic platform tray (sectional elevation).

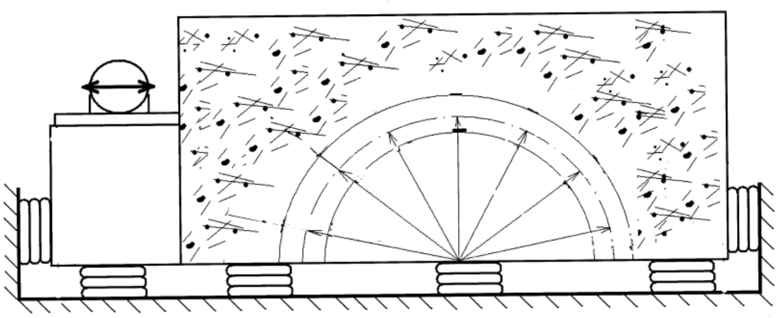

Figure 1. Sectional view of the LSCS arch tested on the seismic platform

During seismic tests we had registered changing the parameters of LSCS dynamic stressed-deformed state and surrounding soil: arch deflections, relative deformation on the corrugation tops and valleys, soil pressure in the LSCS-adjoining back-filling area. Measurements were made in the central longitudinal section of the seismic platform tray in order to decrease the influence of boundary conditions.

Test load input parameters (vertical and horizontal seismic platform motion) were registered by acceleration and displacement sensors, installed on the seismic platform and tray walls.

Comparison of the results of seismic risk improved analysis for the construction site on the basis of explicit data on the geological section structure with predictive evaluations for the construction site had shown the increase of design peak values for horizontal acceleration up to 0,338 g, for vertical acceleration up to 0,203 g, and intensity of maximum seismic input up to 8,8 as per the MSK-64 scale. Reproduction of the received design parameters to required simulation scale was ensured by purposive operation mode selection for the seismic platform drive when testing the LSCS arch structure model.

3. TESTS RESULTS

Figures 2-3 show the accelerogramms of vertical and horizontal design test motion of the seismic platform, received by scaling up according to simulation requirements. In additiin Figures 2-3 presents the process schedules of acceleration time-dependent change of the ground seismic platform tray wall in horizontal and vertical directions in testing. These schedules represent an artificially singled part of substantially more long process of the seismic platform vibrations (45-50 s) and correspond the most active stages of seismic loading – mutual superimposition of impulsive and vibratory components of the vibrations excited.

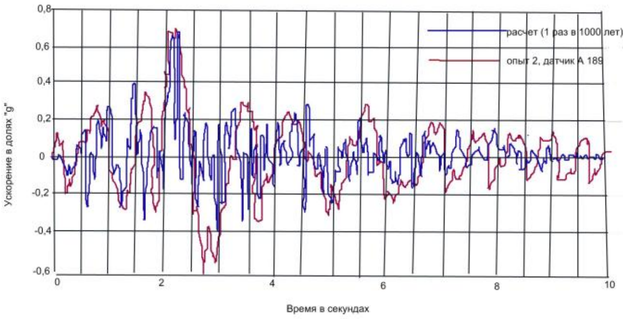

Figure 2. Design and experimental accelerogramms of horizontal seismic platform test motion

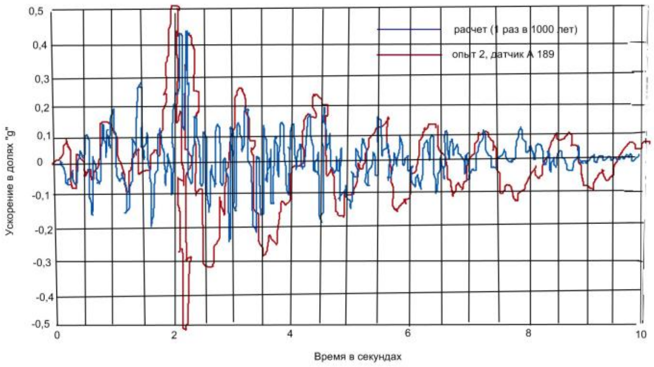

Figure 3. Design and experimental accelerogramms of vertical seismic platform test motion

Comparison of design and experimental accelerogramms in Figures 4-6 shows quite satisfactory fit of frequency-time characteristics of simulated and test seismic loading and peak values of the processes, especially for horizontal component. Duration of the first (vibratory) stage of the seismic platform motion is ~ 12 s, for the second active stage (Fig. 2-3) ~ 12 s, for the whole test process ~ 45 c. Peak load input for the system "LSCS model – soil" is reached practically synchronously with realization of peak acceleration amplitudes of the seismic platform in 13,2 seconds following the process onset.

According to readings the maximum LSCS deflection values along the central cross section perimeter altered within the following range: from 0,30 mm up to -1,0 mm at the first load input phase, from 2,5 mm up to -3,2 mm at the second and from 0 mm up to -0,6 mm at the third stage, peak dynamic stresses in corrugated plates material on the corrugation tops altered from 14,0 MPa up to -6,0 MPa (initial stage), from 24,0 MPa up to -30,4 MPa (the second stage) and from 2,0 MPa up to -6,0 MPa (the third stagee), on the corrugation valleys from 3,0 MPa up to -7,6 MPa, from 24,0 MPa up to -21,0 MPa and from 2,4 MPa up to -3,0 MPa respectively. The soil pressure around the LSCS altered from 8,0 kPa up to -5,0 kPa (initial stage), from 26,0 kPa up to 4,0 kPa (the second stage) and from 5,0 kPa up to -2,0 kPa (the third stagee). It is to be noted, that peak dynamic stresses in corrugated plates material was 10-15 time lower than the design resistance value for steel. Besides, one could see substantial registered parameters growth for the state of the "LSCS arch model – soil" system on the second stage of test load input. For this stage which is of primary interest when test results analyzing the diagrams of parameter maximum distribution in the points of measurement (Fig. 4-6) had been constructed. Deformation diagram of the arch model central cross section is shown in Figure 4. Figure shows that the deformation shape is near antisymmetric relative to the arch normal axis and displacement amplitudes both in the tension area and in the compression area are approximately identical. Likewise dynamic stresses in the corrugated plate material are distributed along the corrugation tops (Fig. 5) and valleys (Fig. 6). Comparison of diagrams in Figure 5 and Figure 6 points relatively large concentration of dynamic stresses on the corrugations tops due to changing geometrical shape of corrugated plate section during their deflection. Also LSCS model examination upon test completion had indicated absence of corrugated plate permanent deformation.

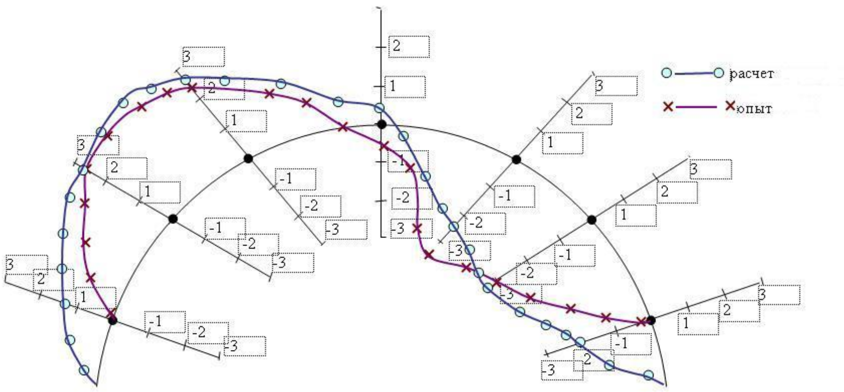

Figure. 4. Design and experimental diagrams of the LSCS central section dynamic deformation (mm) at maximum load input

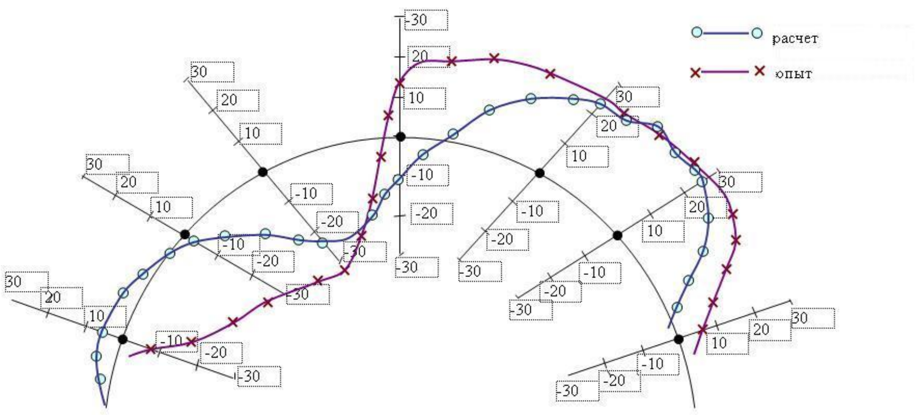

Figure 5. Design and experimental diagrams of dynamic normal stresses in corrugated plate material (MPa) in the LSCS central cross section (corrugation top) at maximum load input

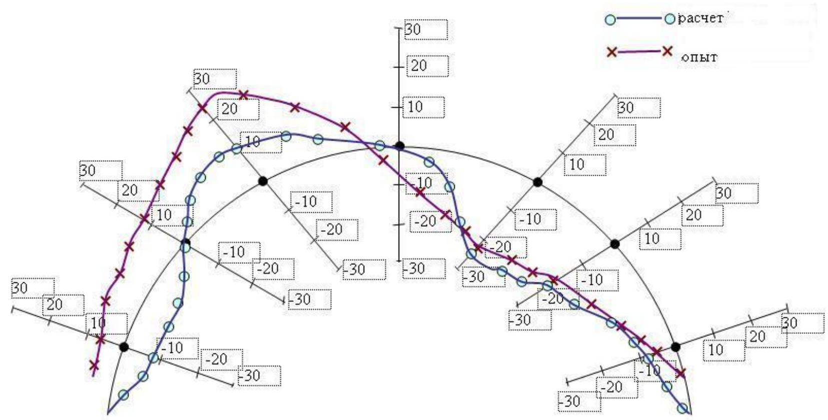

Figure 6. Design and experimental diagrams of dynamic normal stresses in corrugated plate material (MPa) in the LSCS central cross section (corrugation valley) at maximum load input

4. DESIGN -THEORETICAL ANALYSIS OF TEST RESULTS

According to the valid Norms and Standards for large-span LSCS strength analysis under operation of dead, live and dynamic loads, earthquake loading included, we use finite element method (FEM). In our calculation practice we use computer complexes ANSYS and "Zenith-95" These complexes make it possible to realize FEM for embedded nonlinear- deformed modular steel corrugated structures in 3D and plane statements without requirement limitations to the LSCS shape, soil structure with due regard to possible manifestation of plastic deformation in metal and soil.

For numerical experiment when analyzing the test results we had created a 3D finite-element model of "LSCS arch – soil" system, which corresponds the seismic tests conditions for model arch structure made from deep-corrugated plates with wave parameters 381*140 mm on the seismic platform . As the most representative fragment we FEM-simulated a fragment of arch central cross section which included three corrugation semiwaves. The lower part of the arch fragment is fixed on the ground tray base. The shape of corrugated plates and corrugation section corresponds full-scale parameters entirely. Characteristics of the shell arch in the bolt fastening and mutual superimposing zone for corrugated plates has been considered equivalent to major corrugated plate part characteristics.

Design value of soil elastic modulus had been accepted due to evaluation of back-fill physical and mechanical characteristics. As external seismic input during calculations we used registered experimental accelerogramms of active test processes stage, shown for horizontal and vertical component in Figures 2-3.

Seismic input had been applied to the lower and lateral boundaries of the calculation model. General view of the 3D design model is shown in Figure 7. The soil model uses 3D eight-node elements (SOLID45), and LSCS model uses four-node shell elements (SHELL63). For simulation of shell arch and soil interaction we used "surface – surface" contact pairs. All types of elements have been taken from the ANSYS standard library.

Maximum stresses in corrugated plate material are reached in 13,2 s after the test load input (on 1,2 s of the second active stage of motion). Figure 8 shows distribution of normal stresses along its shell derived as the result of embedded arch fragment. The Figure shows that the values of stresses in longitudinal sections of fragment alter substantially both in amplitudes and in sign (compression – tension). Application of 3D calculation model permits finally to determine possibility of ultimate arrival of any arch fragment section into plastic deformation zone. The non-stationarity pattern of stress distribution during seismic tests is to be noted.

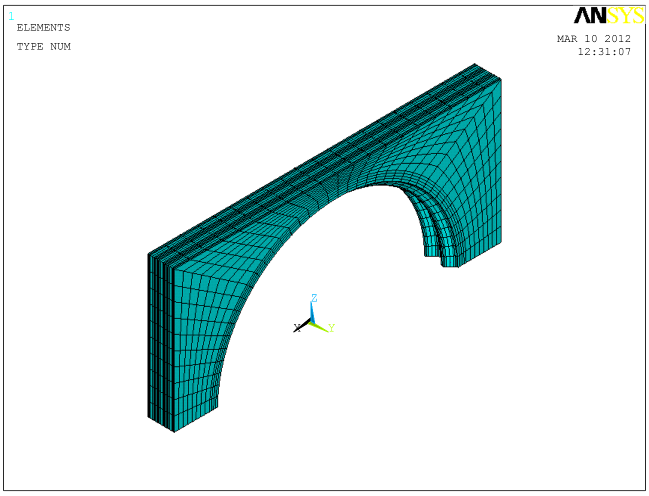

Figure 7. General view of 3D model

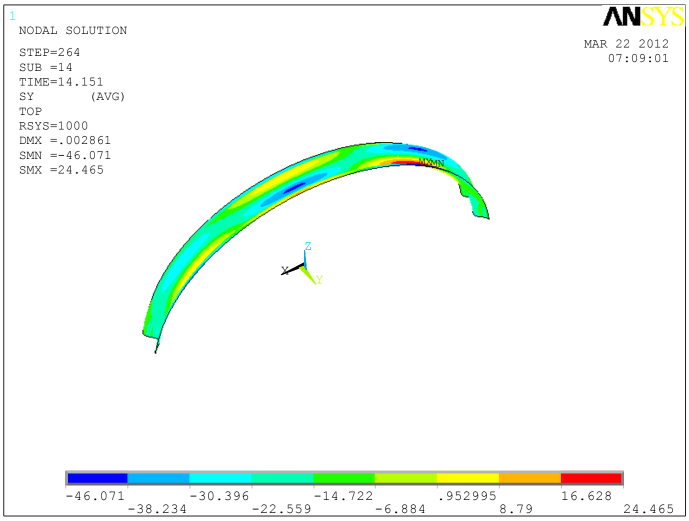

Figure 8. Distribution of normal stresses along the shell

Figures 4-6 present the design and experimental diagram of dynamic displacements (Fig. 4) and dynamic normal stresses on the lines of corrugation tops (Fig. 5) and valleys (Fig. 6). Diagrams were received by way of alignment of peak parameter amplitudes according to records and corresponding calculation data sample. Figure 4 makes it possible to note quite satisfactory coincidence of experimental and design evaluations of dynamic displacements at lowered value of the soil elastic modulus with the exception of LSCS model attachment zone to the base of seismic platform ground tray. Measurement results point the larger demanding influence of the support structure, than is accepted in the design model. For the dynamic normal stress diagrams (Fig. 5, 6) we had received practically satisfactory consent on that half of arch where pneumatic actuator load was applied, further development of more detailed model of active and reactive soil pressure on the contact with movable wavy steel surface is expedient.

At the same time a calculation using 3D model allowed to receive enough test-close peak amplitudes of dynamic stressed-deformed state parameters of LSCS arch structures both for displacements (3,0 mm - in test, 3,05 – in calculation) and for stresses (28,0 MPa - in test, 26,0 MPa – in calculation). These data are reference at earthquake resistant designing of back-filled arch for a protective gallery.

On the basis of data transfer results of model (simulation scale 1:2) bench seismic tests and design theoretical analysis the peak deflection for the arched LSCS with 381*140 mm corrugation at a seismic input will not exceed 6,1 mm, and dynamic normal stresses which are additional to static in corrugated plate material will not exceed 30 MPa.

The correctness of conclusion on high seismic stability of the developed protective gallery structure is strict provision of LSCS arch basement supports and their strength factors.

5. CONCLUSIONS

1. For experimental check of fulfilling the protective gallery seismic stability requirements which had been designed for construction in the immediate vicinity of the river bed (city of Sochi), seismic tests on seismic platform had been conducted. The tests had been performed for a large-scale model (1:2 of natural scale) of LSCS back-filled arch structure fragment with large-sized corrugation 381*140 mm made by Gidromontazh Company. The model diameter was 5,0 m, the height was 2,5 m, the total mass of the LSCS arch and back-fill exceeded 120 tn. In Russian practice such tests have been conducted for the first time.

At experiments statement full simulation requirements of the gallery real structural design and two-component effect (both horizontal and vertical) expected for site design earthquake are observed.

2. The tests had confirmed high seismic stability of the design solution accepted for a LSCS back-filled gallery with corrugation 381*140 mm. According the data on transfer of test readings to full-scale condition due to the simulation rules the peak value for dynamic deflection of the LSCS arch shell will not exceed 6 mm, peak value of dynamic normal stresses - 30 MPa. These values are substantial lower (10-15 times) than allowable by standards.

3. Design theoretical analysis of test results had shown, that developed 3D design models for a back-filled LSCS arch with corrugation 381*140 mm permit to receive reasonable description of dynamic load input of the "LSCS arch - soil" system at non-stationary two-component high intensity seismic input. Comparison of the design and experimental data had revealed peculiarities of dynamic displacement distribution for lateral arch points, dynamic normal stresses along the lines of corrugation tops and valleys, pressure field formation in the soil near arch shell, verification conditions of the design models had been determined. Quite satisfactory conformity between the test data and calculation denotes expediency of using 3D finite-element model for carrying out calculations at seismic design of LSCS with large-sized corrugation in spite of its increased labour input.