Design and construction features on weak clay soils with high seismic hazard. The case of Olympic facilities in Sochi

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Abstract. The article describes the experience of designing and construction the Olympic facilities in Sochi-2014 in difficult engineering and geological conditions, including on weak clay soils, with a seismicity of 9 points. Specific examples of design solutions and their implementation are given, as well as geotechnical monitoring data.

1. Introduction
For the construction of Olympic facilities (sports complexes, an Olympic village, hotels and other facilities) in Sochi, the Imeretinskaya lowland was chosen (figure 1) – the only area that is undeveloped between the Mzymta and Psou rivers.

![Figure 1. Imeretinskaya lowland before the construction of the Olympic facilities.](image)

During preliminary site investigation, the reason became clear – extremely difficult engineering-geological conditions with a high level of a seismic hazard: from the surface to a depth of 30 m, the engineering-geological section is represented by weak water-saturated alluvial sediments, partially peaty, clay and sandy soils of low bearing capacity (figure 2), and in the immediate vicinity of the sea, there is a relatively narrow strip, where a mature layer of gravel and pebble deposits lies shallow under the earth's surface [1].
In this regard, depending on the loads, the location demonstrated, the deep of substructure, different types of foundations are used. The general layout of the Olympic facilities is shown in figure 3.

Currently, the following principles to reduce the impact of earthquakes on buildings are used [2, 3]:
- improvement of soil properties;
- change in the strain-stress distribution of soil massifs, which are as a result of an earthquake, for example, a decrease in the level of groundwater or sub-soil drain device;
- reduction of damage to objects by constructive measures (construction of pile foundations to transfer the load to more durable soils; strengthening of foundations, control of deformations after seismic effects; absorption of deformations by flexible joints, etc.).

In the work of Sato et al [4], various methods aimed at reducing the impact of earthquakes, including the device are considered and compared:
- pile drain to reduce pore pressure;
- a retaining wall that restrains the movement of soil, except for the transfer of pressure to the grillage;
- grillage of an original design with a conical end to reduce the horizontal soil pressure.

As a result, it was found that the latter method has the greatest effect.

Also recently, several innovative methods have appeared that reduce the risk of seismic impacts. The use of silica for binding sandy soil particles should be highlighted here [5, 6]. Rasouil [7] describes the effectiveness of using silica in construction at an international airport in Japan. To improve soil conditions, new, biochemical technologies were used. Dejong [8] summarized these technologies, and it was found that at least two of them have great potential for the usage.

One of the technologies is to use bacteria to form rigid bonds between particles due to the calcium carbonate secreted by the bacteria (this study was carried out by Van Meurs [9]).

Another technology involves the use of gas released by bacteria (biogas effect) [10], which leads to a saturation of pore water with gas, forming a kind of dampers inside the soil mass. For this, it is proposed to inject a special composition into the soil to activate the activity of bacteria to release gas.

Later, there will be several examples of the design and construction of Olympic facilities considered: the building of the Organizing Committee of the Olympic Games in Sochi; Media centre; hotel complex ‘Russian Seasons’, underground utilities, in which different design approaches were applied in a seismic area in soft clay soils.

2. Design and construction of the building of the Organizing Committee of the Olympics Games in Sochi 2014

The building consists of a 9-storey main section and the surrounding 3-storey sections (figure 4). There is a one-level underground car parking under the entire building. The central 9-storey part of the building is similar to the shape to a trefoil (the width of the ‘leaf’ is 18.7 m). The high-rise part of the building is divided into anti-seismic blocks, located on a solid slab grillage. The structural scheme of the building is a frame, with stiffness diaphragms in each anti-seismic block. The main load-bearing structures of the building are made of monolithic reinforced concrete. The dimensions of the construction site in the plan are 120 × 90 m. The average design distributed load on the base from the 9-storey part is 200 kPa, from the 3-storey part – 100 kPa.

The site of the Institutional Building of the Olympic Games Organizing Committee should be recognized as one of the most unfavourable in terms of engineering and geological conditions, therefore, the experience of constructing this building will be considered in more detail.

Geotechnical conditions are shown in figure 5, soil characteristics are demonstrated in table 1. A most difficult was the fact that soft-plastic and fluid-plastic clays of extremely low strength (EGE 2 - 5) with a deformation modulus of 0.7 ... 3.0 MPa lie at a depth of 4.5 ... 21 m below the base of the grillage. At a depth of 9 and 17 m, separate boreholes have exposed peat lenses. Coarse sands occur from a depth of 21 to 23 m (IGE 6), and from a depth of 23 m — gravel-pebble soil. Clay soils of the site are characterized by organic matter content up to 10 ... 15%. 

Another factor was the seismic activity in the area of construction. According to SNiP II-7-81 (as in force in 2000), the background seismicity of the entire study area is 8 points for mass construction (map OSR-97, A). The soils taking part in the geological structure of the Imeretinskaya lowland and occurring in a 10-meter layer of sediments belong to the III category in terms of seismic properties.
Taking into account soil conditions, the seismicity of the central part of the territory was 9 points for mass construction.

| Geological index | EGE number | Description of soil                                                                 | Soil density (kN/m$^2$) | Angle of internal friction (deg) | Specific cohesion (kPa) | Modulus of deformation (MPa) |
|------------------|------------|--------------------------------------------------------------------------------------|--------------------------|---------------------------------|-------------------------|-----------------------------|
| lgQIY            | 1          | Bulk unconsolidated soil: gravel, pebbles and crushed stone with sand aggregate, wet | -                        | -                               | -                       | -                           |
|                  | 2          | Clay with an admixture of organic substances, hard-plastic                           | 17.1                     | 12                              | 22                      | 3                           |
|                  | 3          | Clay with an admixture of organic substances, slightly peat, soft plastic            | 15.9                     | 10                              | 11                      | 1                           |
|                  | 4          | Clay with an admixture of organic substances, slightly peat, with interlayers of sand, flowable plastic, with interlayers of a flowing consistency | 15.2                     | 10                              | 11                      | 0.7                         |
|                  | 5          | Medium decomposed peat, saturated with water                                         | 11.9                     | 13                              | 16                      | 0.9                         |
| mQIY             | 6          | Coarse sand, with sparse gravel, dense, saturated with water                         | 20.9                     | 36                              | 1                       | 37                          |
|                  | 7          | Gravel-pebble soil with sandy aggregate saturated with water                        | 21.2                     | 38                              | 2                       | 53                          |

Another negative factor was the flooding of the territory – the entire Imeretinskaya lowland is in a highly flooded state. The groundwater level at the time of the survey was maintained only with the help of drainage and constant pumping of drainage water into the sea. In the absence of pumping, the central part of the lagoon depressions of the lowland should have been in a flooded state.

Taking into account the engineering and geological conditions, an uncontested constructive solution was made – a pile foundation. At the stage of choosing the type of piles there were considered the following ones: prefabricated reinforced concrete piles, bored piles, jet-piles, crushed stone piles in a shell of geosynthetic materials, etc. The technical and economic comparison of the options made it possible to choose the most economical option – prefabricated driven piles.

It is known that taking into account the stability of the pile foundation under the seismic impact, it is required to ensure the perception of the entire horizontal seismic load by the piles. However, on site a soil layer capable of creating any significant resistance to horizontal load (and also vertically) lies at a depth of more than 21 m horizontal. Calculations showed that for the perception of the vertical load from the 9-storey part of the building, 511 piles with a cross-section of 35x35 cm are needed, and for the perception of the horizontal seismic load – 2030 pieces, i.e. 4 times more.

Having studied the experience of designing pile foundations in our country and abroad, including post-Soviet states, it was possible to find out that foundations with an intermediate pad were initially used in Chile, then they were used in construction in the USSR by D.D. Barkan and Yu.G. Trofimenkov [11] and were massively used in the 1970s – 1980s. At that time, in the USSR and later in the Russian Federation, recommendations on the use of foundations with an intermediate pad in areas with seismicity of 7, 8 and 9 points [12-14] were developed and the application of these
foundations [15, 16], the foundations for calculating pile foundations with intermediate cushion for seismic regions were investigated [17, 18]. As a result of experimental work, it was found that when using an intermediate sand cushion on the piles, the horizontal seismic load is practically not transmitted.

![Figure 6](image).

Figure 6. Dependence of the foundation settlement on the thickness of the sand cushion above the pile heads.

A much more effective measure is the increase of the head width (figure 7).

![Figure 7](image).

Figure 7. Dependence of foundation settlement of the pile head width.

At the same time, it was impossible to apply such a structure without changes on the site, and since the norms do not allow its use in the presence of soil with an organic matter content of more than 10%, in collapsing soils, in seized territories, etc. risk of subsidence of the loose soil of the intermediate pad. However, since the approval of the norms and the ban on the use of a pile foundation structure with an intermediate pad, new materials (geosynthetics) in these soils, which are very widely used in construction appeared. Therefore, it was proposed to reinforce the intermediate pad with geosynthetic
materials [19], for which, in the development of the current standards, the calculation method, taking into account the elastoplastic properties of the foundation soils, the effect of piles in a group, geometric and stiffness characteristics of the elements of deep foundation supports (pile heads reinforcing geogrids, etc.), stiffness parameters of foundation slabs (slab grillages), seismic conditions of the construction site, etc. was modified.

In the case of a head with a width of 1 m, the sediment is reduced by more than 2 times at a pressure under the subgrade of the slab of 100 kPa and more than 4 times at a pressure under the subgrade of 300 kPa. With an increase of the head size, the effectiveness of the event decreases and the difference between a solid slab (for example, a head with a width of 2 m) and a head with a width of 1.4 m is minimal. An increase in the thickness of the rammed soil along the bottom of the pit from 0.3 to 2 m leads to a decrease in settlement by 13 ... 16%, which is due to the involvement of the soil from the backfill of the lateral surface of the piles into the work.

Using the dependencies obtained in the analysis of the cushion for the 9-storey part of the building, the option of the foundation for the 2-storey part of the building with a twice as large pile pitch (one pile accounts for 8 m2 of the foundation area), with 1.4 m wide heads and with a reinforced geogrids with sand and gravel cushion 800 mm thick was considered. The thickness of the cushion was chosen to be 800 mm to compensate the difference in the thickness of the slabs of the 9-storey and 2-storey parts of the building.

After confirming the reliability of the foundation for vertical load, a horizontal load test was performed. The calculation of the foundation for shear along the sole following SP 22.13330 (clause 5.7.12) based on the condition was carried out.

\[
F_{s,a} \leq \left( y_c \cdot F_{s,r}\right)/y_n, \tag{1}
\]

where \(F_{s,a}\) and \(F_{s,r}\) are the sums of projections onto the sliding plane, respectively, of the calculated shear and holding forces; \(y_c\) is coefficient of working conditions, taken for sands, except for silty sands equal to 1; \(y_n\) is the reliability factor for the structure, taken equal to 1.2 for structures of the I level of responsibility.

By calculating the sum of the projections of the shear and restraining forces, it was found that the shear stability along the base, taking into account the seismic effect, is provided with a margin of 1.67 (stylobate) and 5.53 (high-altitude).

The foundation design accepted is shown in figure 8.
Figure 8. Construction of the foundation under the 9-storey (a) and 3-storey (b) parts of the building.

Under the 9-storey part of the building, the pile foundation consists of piles with a cross-section of 35×35 cm and a length of up to 22 m, located on a square grid with a step of 2×2 m (figure 9), and under a 3-storey part — with a step of 4×4 m. The dimensions of the heads were 1.4×1.4×0.4 (h) m.

Figure 9. Upper part Pile trimming, setting up a concrete head and filling a sand cushion with compaction.
The intermediate pad was adopted with a thickness of 600 mm with reinforcement with two layers of the Fortrac 35MP geogrid. The bottom layer of the geogrid is laid directly on the heads, and the next layer in the thickness of the pillow — at a distance of 300 mm from the top of the heads. The thickness of the slab grillage under the 9-storey and 3-storey parts of the building was 800 and 600 mm, respectively.

During the construction, geotechnical monitoring was carried out, during which there was measured the settlement of the foundations and layer-by-layer soil deformations of the sand cushion. The layout of geodetic marks on the walls and columns of the building and marks for measuring the displacement of the soil mass under the foundation slab (Tr - 1 and Tr - 4) is shown in figure 10.

![Figure 10. Scheme of geodetic marks placement on the walls of the building.](image)

As a result, it was obtained that the maximum settlement of 9-storey parts of the building was 20 ... 80 mm (figure 11), 3-storey — up to 170 mm.
To measure layer-by-layer displacements under the foundation slab, soil marks were installed both on the surface of the heads and on the border of the sand cushion with the natural soil massif (figures 8 (b) and 12).

The monitoring has showed that the movement of marks on the pile head and on the border of the sand cushion with the natural soil massif at the first stage are close (figure 13). Then, at the second
stage, a greater increase in the settlement of the mark installed on the pile head is observed. Further, after final compaction the settlements were fitted at the third stage.

![Graph showing vertical displacements of benchmarks](image)

**Figure 11.** Vertical displacements of benchmarks 71 and 206 of block 9b.

![Images of marks for measuring displacement](image)

**Figure 12.** Marks for measuring the displacement of the soil of the head above the pile under the foundation slab: (a) – side view; (b) – top view. The discrepancy in sediments at the second stage occurred as a result of the fact that at this stage the predominant part of the load was perceived by the head as a more rigid structure in comparison with the filling made of sand and gravel mixture, which was not sufficiently compacted between the heads. At the third stage, after the additional compaction of the sand and gravel mixture, the pressure and settlements became equal (figure 13).

It should be noted that the monitoring of the Tr4 brands at the second stage was terminated due to their damage during the construction and installation work. The results obtained confirmed the correctness of the adopted constructive decision on the construction of heads and a reinforced sand cushion during construction on soft soils in the seismic zone.
The very construction of the foundations and the enclosing structure of the excavation was complicated because of heavy rains in September 2011. Areas of significant displacement of the enclosing structure from driven piles were identified (figure 14 (a)), destruction of temporary concrete and bypass roads and an earthen slope located around the construction site, as well as displacement of the top of individual working piles. During the scientific and technical support, it was found that the movements of the enclosing structure that had taken place since the beginning of construction increased significantly and as of September 26, 2011, amounted to more than 50 cm. Thus, the enclosing structure became insufficiently stable and, on the one hand, pressed on the temporary concrete road, on the other hand, led to the destruction of the asphalt pavement of the soil slope (figure 14 (b)), on which the cabins and warehouses were located, and cracks in the bypass road appeared.

In this situation, the load was urgently removed from the northern part of the enclosing structure: huttages were dismantled along with the enclosing structure, and a slope 5-6 m wide was flattened to a depth of 2 m for collection and drainage of water. Besides, traffic on the bypass road (no more than one car) and the speed of vehicles (no more than 10 km/h) were limited. At the base of the slope, two rows of piles with a length of 20 m were driven with the top of the piles at an angle of 15° towards the slope. To stop the soil slipping on the slope, the soil was filled into its base, and the height of the

![Figure 13. Graph of the development of marks movement on the pile head (Culv. 3 port and Culv. 4 port) and at the border of the sand cushion with an array of natural soil (Culv. 3 strat. and Culv. 4 strat.) in time.](image1)

![Figure 14. Displacement of the enclosing structure (a) and a crack in the asphalt pavement (b).](image2)
filling should not exceed 1.0 m (to avoid soil uplift). Also, to prevent the development of the enclosing structures movements, it was prohibited to dismantle the anchor rods installed to fasten the pit fence (figure 14a: the rods are visible in the foreground).

The significant displacements of the enclosing structure and the slope soil mass have led to serious consequences — the displacement of the piles top of the building foundation pile field. According to engineering and geodetic measurements, the displacement of the piles top was 7 ... 39 mm. Such significant displacements could lead to a decrease in the bearing capacity of the piles and to their destruction when a vertical load is applied. In this regard, additional tests of the piles that received the largest displacements were performed, and calculations of the foundation, taking into account the reduced values of the pile stiffness were repeated. As a result, it was found that the additional foundation settlement, as well as the increase in efforts in the building structures, did not exceed the limit values.

To obtain operational information on the state, daily monitoring of the vertical and planned position of the enclosing structures, soil marks installed on concrete and bypass roads, the top of the foundation piles, and for the piles along which the tops were made — along their centre was organized. Urgently organized work in order to prevent further movement of the enclosing structure made it possible to rectify the situation and the static load tests of two piles that fell into the zone of displacement of their top confirmed the design bearing capacity of the piles.

Design solutions and specific measures for scientific and technical support at the construction site made it possible to put the Olympic Committee building into operation on time with excellent quality.

A assembly view of the Olympic Committee building after construction completed is shown in figure 15.

3. Design and construction of the Media Center building
During the construction of the Main Media building Center of the Winter Olympic Games (hereinafter the Media Center), a foundation slab was used (figure 16) [20, 21].

The building of the Media Center is a 2-3-storey building with has the size of 423×394 m. The supporting structures are a reinforced concrete frame, the column spacing is 8.1×8.1 m (figure 17). The average pressure along the foot of the foundation is 0.6 - 0.8 MPa.

At the base of the foundation lies a large stratum of weak soils (IGE 5, 15), with a deformation modulus of 1.6 .. 6.3 MPa. The characteristics of the soil are shown in Table 2, a typical Geotechnical cross-section is shown in Figure 18.

![Figure 15. Olympic Committee building after completion of construction.](image-url)
Considering the large area of the building and the relatively low loads on the foundation, a foundation slab on an artificial foundation with a height of 2.8 - 4.0 m, reinforced with two geogrids, as a foundation was used.

Figure 16. Assembly view of the building of the Main Media Center of the Winter Olympic Games in Sochi.

Figure 17. The interior of the building of the Main Media Center of the Winter Olympic Games in Sochi.
The construction of the artificial base is as follows (figure 19):
1) crushed granite grade 600, fraction 25-60 mm;
2) Geogrid Triax170;
3) gravel-sand mixture;
4) crushed granite grades 800 ... 1000, fraction 20-40 mm;
5) Triax170 geogrid on a natural base.

It should be noted that within the framework of the engineering preparation of the territory of the Imeretinskaya lowland for the construction of Olympic facilities to avoid flooding, the work to fill the territory to a height of 4 m was carried out. The works on the construction of an artificial foundation
were included in the scope of engineering training, thus the design solution for the foundation of the Media Center was significantly reduced.

It is worth mentioning to describe the experience of arranging the specified dumping of the territory. Initially, it was decided to store the dumping soil in separate dumps, large in volume, which can be used on a large area of the territory. This seemed convenient and technologically advanced, but there wasn't taken into account the very weak soils located under the surface — their bearing capacity was insufficient to absorb the soil pressure of the dumps. There was a flooding of the soil located around the dump, and the value of the flood reached 300 ... 500 mm, and it was fixed with the naked eye. The diagram of the formation of soil upheaving during filling is shown in Figure 20, and the height of the embankment during the upwelling did not exceed 3-4 m (!). This testifies to the very low bearing capacity of the foundation soil of most of the Olympic venues in the Imeretinskaya lowland.

![Figure 20. Diagram of the soil swelling formation during filling: 1 – an in-situ cross-section of the embankment; 2 – the actual outline of the embankment; 3, 4 – the base of the embankment before and after the soil flooding; 5 – protrusion of the base.](image)

Special surveys carried out to study the compaction of such soils showed that they are prone to a long process of consolidation, and there is an initial filtration gradient and high deformation values under load [20, 21].

Subsequently, such studies were carried out at other facilities, as well as directly during the construction of the Media Center. Fearing the manifestation of the described processes, in the foundation design, in addition to the device of a reinforced artificial foundation, a rigid foundation 1000 mm thick made of concrete of class B30 on a reinforced concrete preparation with a thickness of 100 mm was chosen, cut into 49 compartments with a maximum size of 56.7×56.7 m (figure 21).

Sedimentary joints cutting the foundation slab were aligned with anti-seismic joints dividing the Media Center into a series of separately deformable blocks. Seams 50 mm wide were filled with PSB-S 50 polystyrene foam. At the edges, a cyclotherm cord and polyurethane sealant were provided. Waterproofing of foundations — one-layer 'Isoplast P' lining.

During construction and subsequent operation, geodetic monitoring of the foundation settlement of each compartment was carried out. The layout of the stamps for this is shown in figure 21. As a result, it was found that precipitation for 2600 days in some compartments (figures 22 and 23) reached 1400 mm (!). At the same time, in the process of erection of foundation slabs and structures of buildings, settlements occurred unevenly. So, when visiting the construction site in October 2011, it was recorded that the difference in the heights of the foundation slabs tops of adjacent compartments was more than 200 mm (figures 24, 25, 26).

To avoid distortions of the floors during operation, the levelling filling of the foundation slabs top with a layer of expanded clay was performed, after which the floors were already arranged on it. This technical solution turned out to be very successful, and there were no difficulties during the operation of the Media Center.

The right decision was confirmed in 2016 when examining the state of the building structures (figure 27). As a result, it was revealed that they are in good condition, except for a few places where cracks on the floor at the location of the expansion joint were found.
Figure 21. The layout of partitions compartments and benchmarks for monitoring.

Figure 22. Graph of the development of the partition sediment 11 in time.
Figure 23. Graph of the partition sediment development 16 in time.

Figure 24. View of the joint between foundation slabs (October 2011).
4. Design and construction of the Russian Seasons hotel complex

The project of the Russian Seasons hotel complex included 12 multi-storey (up to 8 floors) buildings and ones of the public and entertainment zone (see figure 27). Each of the hotel buildings consists of two interlocked sections with the size of $36 \times 14.9$ m [22].

The geotechnical conditions of the site due to the large area are highly variable in a plan. Engineering-geological bedding (from top to bottom) is represented by fill soils with a layer thickness of up to 4 m, peat, silt and water-saturated dusty sands, underlain at various depths from the surface (from 3 to 11 m) by gravelly sands and gravel-pebble soils.
For the foundation, driven reinforced concrete piles with a cross-section of 30×30 cm and a length of 4 - 12 m were used. The length of the piles is due to the deepening of their lower ends into the bearing layer of gravelly sands and gravel-pebble soils by at least 0.5 m.

There were used two types of foundations (figure 28 a, b) [22].

**Figure 28.** Pile foundations of the hotel complex buildings: (a) – type I (with an intermediate ground pad); (b) – type II (with rigid pinching of the piles into the slab); 1 – reinforced concrete driven piles; 2 – geotextile; 3 – reinforced concrete head; 4 – sand and gravel cushion; 5 – concrete preparation; 6 – reinforced concrete foundation slab; 7 – waterproofing cord type WATERSTOP

Type 1 – a solid foundation slab 400 mm thick with thickenings under the load-bearing structures up to 800 mm, levelled at the bottom, on a pile foundation with an intermediate sand and gravel cushion, similar to the type of foundation used on the building of the Olympic Organizing Committee. As it was already described earlier, the intermediate pillow practically excludes the transfer of horizontal loads to the building foundation, arising from seismic influences. An intermediate pad 0.75 m thick from local sandy and sandy-gravel soils with layer-by-layer compaction is poured over piles with reinforced concrete heads. Geotextile was laid on the surface between the piles, which goes under the headings. The pile is connected to the head through a layer of impact-resistant polystyrene.

Type 2 – for a part of buildings, at the base of which peat or peat soils with a modulus of deformation $E = 5 \ldots 6$ MPa lay, a solid foundation slab of variable thickness, levelled on top, with rigid pinching of the piles into the slab was designed. At the same time, piles that perceive the action of horizontal seismic loads have intense reinforcement following the requirements of regulatory documents.
The pile field is designed for the main and special (seismic) combination of loads. The design load on piles with the basic combination is 75 tons, with a special combination — 100 tons. The ability of piles to take a load of 100 tons is confirmed by the results of tests with static loads. The calculated horizontal load on the piles at rigid conjugation of the piles with the grillage does not exceed 3.5 tons.

As mentioned earlier, the engineering-geological conditions of the construction sites adjacent immediately to the coastal strip of the Imeretinskaya lowland are more favourable: weak clay deposits or biogenic soils in these areas are either absent at all, or their thickness is insignificant. As an example of construction in the coastal strip, one can cite the project of a 6-7-storey hotel complex and an apart-hotel on site D1, the location of which is shown in figure 29.

![Location of the D1 site in the coastal zone.](image)

The premises of the hotel, apartments and auxiliary services are arranged in one building, divided by expansion and anti-seismic joints into separate sections (figure 30).

![The layout of the foundation slabs of the building on the site D1: (a) – pile foundations; (b) foundations on a natural foundation.](image)
Since the building occupies a large area in the plan, the geotechnical conditions of the site are different even within the building area. This circumstance revealed the need to use different types of foundations within the same structure.

In the area located close to the coast, the engineering-geological section is represented by thick deposits of coarse and gravelly sands underlain by gravel-pebble soils. For these areas, the foundation in the form of a monolithic slab on a natural foundation with a thickness of 400 mm with thickenings up to 800 mm under the supporting structures is designed. Farther from the coast, from the surface, there are weak technogenic soils, which by the beginning of construction were covered with an embankment made in the process of engineering preparation of the territory. This excluded the replacement of technogenic soils, as a result of which, it can minimize the difference in the settlement between the various deformation blocks of the complex, in these areas, the project provided for a pile foundation with an intermediate pad, similar to the previously described technical solutions.

5. Design and construction of underground water-carrying communications

The massive construction of Olympic sports and all kinds of auxiliary facilities required the installation of a multi-kilometre network of various underground water-carrying communications — heating system, water supply system, household and rainwater drainage systems, differing in the principle of liquid transportation (gravity, pressure), pipeline material (steel, polyethylene, polypropylene), pipe diameters (250 ... 1580 mm).

In the difficult engineering and geological conditions of the Imeretinskaya lowland, the main problem in the design of the bases and foundations of communications was the possible significant uneven settlements of weak clay soils and additional sediment from the loads arising from the filling of the territory. According to the predictive calculations of NIIOSP [22], the sediment of a 5 ... 20-meter thick layer of soft soils could be 180 ... 720 mm and occur over several months or years, and this even when using special geotechnical methods to accelerate soil consolidation (sand or geosynthetic drains, temporary loading bedding, etc.). It was also impossible to use other methods of soil stabilization (stone columns, soil reinforcement, stabilization with jet elements, etc.) for financial reasons and due to the lack of time.

For such a large-scale design of underground communications, NIIOSP specialists have developed special recommendations for various communications with an indication of the maximum acceptable deformations, which made it possible to select the most effective types of bases and foundations for all various communications in the shortest possible time (table 3) [22].

| Table 3. Maximum allowable deformations of the engineering communications foundations. |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Type of testing calculation     | Engineering communications       |                                 |                                 |                                 |
|                                 | Delivery line                   | Self-flowing communication      |                                 |                                 |
|                                 | Water supply system             | Heat network (steel)            | Household sewerage (polypropylene) | Rainwater drainage (polypropylene) |
| Checking the strength of pipelines | \( r \geq r_{min} = 50 \text{ m} \) | \( r \geq r_{min} = 400 \text{ m} \) | -                              | -                              |
| Inspection of pipeline self flow condition | -                              | \( i \geq i_{min} = 2.5 \cdot 10^{-3} \) | \( i \geq i_{min} = 0.8 \cdot 10^{-3} \) | -                              |
| Pipeline sealing inspection     | -                              | \( \varphi_{max} \leq 10 \)     | \( \varphi_{max} \leq 10 \)     |                                 |
| Experiment on crack resistance of reinforced concrete protective ditch | -                              | \( r \geq r_{min} = 16.7 \text{ km} \) | -                              | -                              |

Notes: \( r \) and \( r_{min} \) — calculated and minimum allowable radius of curvature of the pipeline; \( i \) and \( i_{min} \) — design and minimum allowable slopes of the pipeline; \( \varphi \) and \( \varphi_{max} \) — calculated and maximum permissible angles of rotation in the joints of the pipeline.
These recommendations had to be fulfilled since in the Russian regulatory documents there are no maximum permissible deformations concerning communications. The approach adopted was based on the calculations of communications for the limiting states.

As a result, part of the communications was designed on driven reinforced concrete piles, part – on strip foundations of monolithic reinforced concrete on a natural or artificial foundation, arranged by completely or partially replacing weak lagoon deposits with sand and gravel mixture (figure 31) [22].

![Figure 31. Solutions for the footings and foundations of underground water-bearing communications laid in the area of st. 19 on the territory of the Imeretinskaya lowland. (a) – foundation made of driven reinforced concrete piles; (b) – reinforced concrete strip foundation on a natural foundation; (c) – reinforced concrete strip foundation on an artificial (complete replacement of weak soils with a sand and gravel mixture) foundation; 1 – sandy and gravelly soils; 2 – weak clay soils; 3 – reinforced concrete strip foundation; 4 – reinforced concrete driven pile; 5 – reinforced concrete grillage; 6 – sand and gravel bedding; 7 – replacement of weak soils with sand and gravel mixture; 8 – pipeline in the protective channel; 9 – pipeline covered with sand with geotextile wrapping; 10 – backfilling with sandy soil.](image)

6. Conclusion
Thus, in the design of the Olympic facilities in Sochi, various design solutions were applied: from replacing weak soil with a sand cushion to pile foundations; with the transfer of the load directly from the grillage to the piles and with the transfer of the load through the sand bed. The monitoring results for more than 5 years have confirmed the decisions taken.

Further research can be directed to the application of the innovative methods described in the Introduction, aimed at combating soil liquefaction by increasing the cohesion of sandy soils using silicatization or the activity of a certain type of bacteria. The use of bacteria is also possible to saturate the pore water with gas, which will act as a damper to reduce seismic impact.

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