Geotechnical Features of Sochi Olympic Facilities Project Designs

Les aspects géotechniques de la conception des installations olympiques de Sochi

Petrukhin V.P., Kolybin I.V., Budanov V.G., Isaev O.N., Kisin B.F., Bokov I.A.

Gersevanov Research Institute of Foundations and Underground Structures (NIIOSP), Moscow, Russia

ABSTRACT: The key facilities of the XXII-th Olympic Games 2014 in Sochi have been erected on the Imeretin lowland, characterized by complicated geological environment and high seismicity. Leading Russian organizations have been invited to tackle the related geotechnical issues. The paper describes specific aspects of geotechnical design of the Olympic facilities. There have been reviewed project design solutions for the footings of buildings, structures and underground service lines, developed either by NIIOSP or with its participation.

RÉSUMÉ : Les importantes installations des XXII^{èmes} Jeux Olympiques de Sochi en 2014 ont été réalisées dans la plaine d'Imeretin, caractérisée par un environnement géologique complexe et une sismicité élevée. Les autorités Russes ont été invitées à résoudre les problèmes géotechniques posés par ce projet. Cet article présente les particularités de la conception géotechnique des ouvrages Olympiques: les solutions adoptées pour les projets de fondations, de bâtiments et de lignes des services, développés par le NIIOSP ou avec sa participation.

KEYWORDS: OLYMPIC FACILITIES, IMERETIN LOWLAND, DESINGING, FOOTINGS, SOFT SOILS, SEISMICITY.

1 INTRODUCTION

In 2014 Russia will host the XXII-th Winter Olympic Games and the XI-th ParaOlympic Games to be held in Sochi which has humid subtropical climate.

The Olympic sports and infrastructure facilities are divided into two clusters: coastal and mountainous. The paper is dedicated to the geotechnical issues of Olympic facilities erection in the coastal cluster, which includes 6 main sport palaces, IOC quaters, hotels and tourist attractions. The coastal Olympic cluster is located on 1240 Ha up to 2 km wide Imeretin lowland terrain that extends 7 km along the coast (Fig.1).

The terrain is protected against cold winds by the Greater Caucausus Mountain Ridge so the winters here are not cold. The area features subtropical climate of Mediterranian type. Mean annual air temperature is + 13,7º C. The coldest month is January with mean air temperature + 5,3º C.

The mountainous cluster, where ski and biathlon competitions will be held and a ski jump and a bobsleigh center, are located at 48 km from the main Olympic facilities.

The seaside cluster terrain is a flatland, transferring into a gently sloping hillside piedmont. The geological survey of deposits down to 50 m (Fig. 2) depth revealed occurrence of several lithological features, represented by soft soils (peat, silt, including peat-containing clay soils of liquid-plastic consistence), sand loams, sands (from fine to coarse-grained composition), by gravel and pebble containing soils. Young modulus of soft soil which is present in most of the seaside area rarely exceeds 5 MPa value. Ground water table is just 1...3 m below ground surface.

The area seismicity magnitude is 9 i.e. extreme seismic risk. The soils on the site belong to seismic class II (sand loams, gravel pebble soils) and class III (water-saturated sands and soft clays).

More than 100 various buildings and structures are being built within the area.

The main Olympic sports facilities are erected on 240 Ha. area of "Olympic Park". This is the 40000 seats central Olympic stadium, a 12000 seats Big ice hockey arena, 12000 seats Ice sports palace with 60 x 20 m arena, a training rink for figure skating and for short track skating with 60 x 30 m arena, 8000 seats Indoor skating center, 7000 seats Ice hockey area, Ice arena for curling (see Fig.1). Auxiliary facilities are being built on the western side of the "Olympic Park" – IOC hotel, hotels for the Olympic family and ParaOlympic committee, technical and international zones, a service center. Media Center, 3*, 4*, 5* hotels and various auxiliary buildings are located to the east of the Olympic Park.

The lowland ground is slightly above the sea level, 1,5…4,0 m on the average. Large areas are subjected to flooding and waterlogging. Prior to construction works it was planned to protect the area from waterlogging and preserve existing ground water table. Thus the area was filled up to 2,5 ÷ 3,5 m average level with drainage at the bottom of the fill. The drainage ensures an excess of the fresh ground water table above the sea level that prevents sea water intrusion into the deposit rock. In order to avoid salination of ground water the depth of drainage is limited by at least 0.6 m level above the sea. This condition is maintained by limiting fresh water consumption especially in summer and autumn periods, which may be compensated from water supply system or other sources in the event of overconsumption.

Upfilling the terrain level prior to construction activities in the areas of soft clay soils, peat and peat-containing soils results in long-term settlements due to soft clayey soil consolidation.

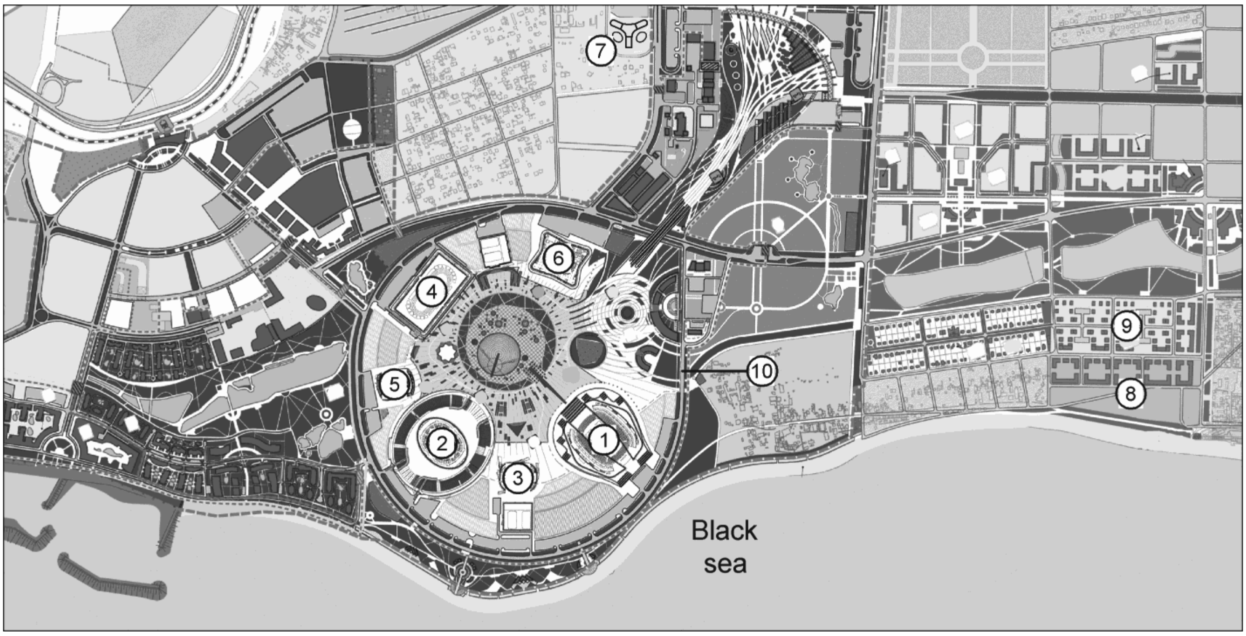


Figure. 1. Overview of Imeretin lowland with indicated construction sites. 1 – Olympic Stadium “Fisht”; 2 – Big Ice Arena; 3 – Minor Ice Arena “Ice Puck”; 4 – Skating Stadium “Adler Arena”; 5 - Curling Center “Ice Cube”; 6 – Winter Sports Palace “Iceberg”; 7 –Organizing Committee Building; 8 – Plot D1; 9 – Plot 17; 10 – Olympic park.

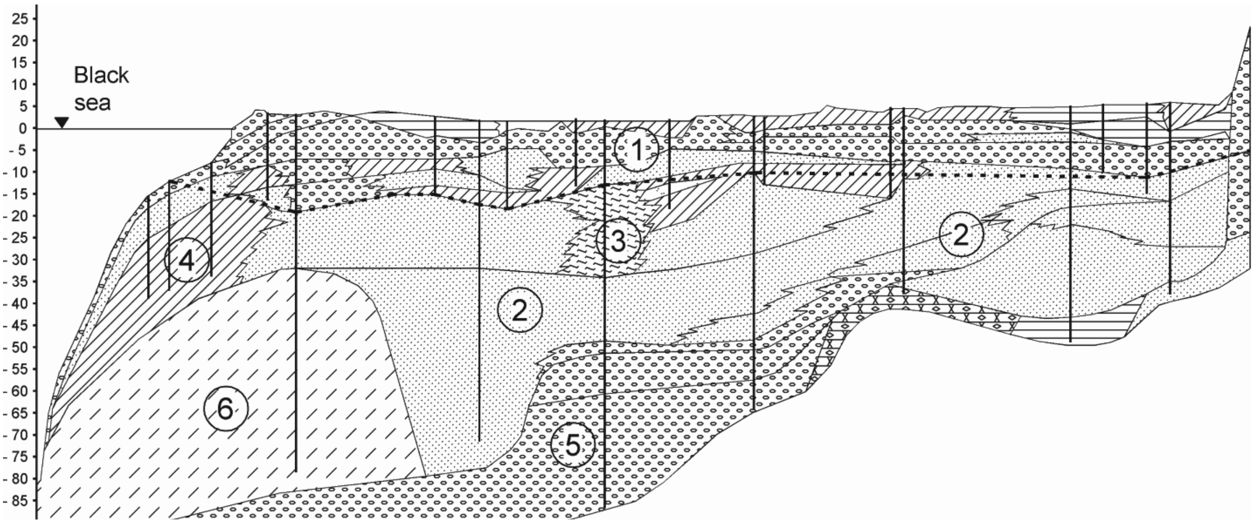


Figure. 2. Typical soil profile for Imeretin lowland.
1 – Interbedding of man-made ground and soft water saturated soils; 2 – Sands with inclusions of peat; 3 – Sands and clays with high peat content; 4 – Loam ; 5- Neogene gravel and pebbles, mudstone; 6 – Sandy loam.

2 THE BIG ICE ARENA

The Big Ice Arena (BIA), having 12000 seating capacity, will be used for competitions and workouts of ice-hockey teams. The arena comprises a complex of facilities, subdivided in to two independent volumes: the Big Arena structure and its stylobate. The stylobate is separated from the main arena by compensation joints. The stylobate periphery is backfilled with soil with access stairs on the soil slopes and drive-in ramparts for access to the building (Fig. 3).

Typical geological conditions of the area are shown on the profile (Fig. 4). Soil on BIA site is essentially better as to their strength and deformation properties than soft soils on other terrains of the Imeretin lowland.

The upper part of the geological profile down to 7,5 m consists of gravelly coarse and medium sands, gravel and pebble soils, having Young modulus of 20…32 MPa, that can ensure footing stability and its admissible deformations, therefore, a raft was preferred as a footing for BIA structure. According to triaxial dynamic compression test results the saturated sands below the building are not sensitive to vibro-liquefaction.

The cast concrete raft of BIA is divided by compensation joints into separate rafts for each structure (Fig. 5).

The raft under the main arena is 1 m thick while it is 1.4 m thick along the 11 m wide ring at locations of staircases and columns, transferring loads from roof cover trusses to the raft. The stylobate raft thickness is 0,6 m, and it is 1 m thick at column supports locations.

The absolute elevation of all footing rafts bottom is 2,3 m. The top soils and soft sand loam soils at the rafts bottom elevations are replaced by compacted crushed stone and gravel fill. The footing is protected from seasonal ground water table rise by local ring drainage system that is included into the system of engineering protection of the area.

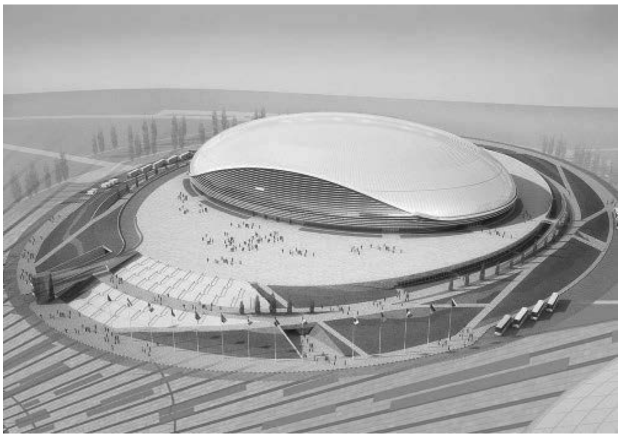


Fig. 3. Overview of Big Ice Arena.

Raft analysis was performed with the account of joint footing-superstructure analysis for the service and ultimate limit states. ULS analysis included the main and characteristic combinations of design loads with seismic action in both directions along the structure main axes. For characteristic combination the analysis included the raft shear along its bottom while for stylobate structures the exess of the vertical component of the design eccentric load over vertical force of limit state force in the case of one-sided soil upthrust, caused by seismic action. Shear verification was done for horizontal force, defined as a geometrical sum of horizontal loads in characteristic combination along the principle axes.

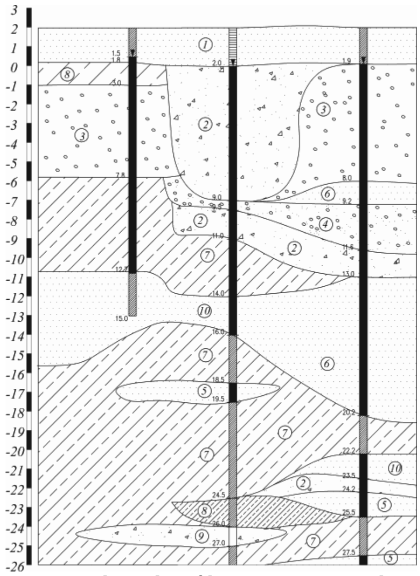


Fig. 4. Arena geological profile: 1. Coarse grained sand; 2. Gravelly soil; 3. Pebble soil with sand fill; 4. Gravely sand 5. Fine to medium sand, with thin seams of sandy clay; 6. Sand; 7. Plastic sandy loam; 8. Sandy loam with pebbles; 9. Gravel and pebble mixture; 10. Fine sand.

The values of loads, applied to the footing rafts, were determined with the account of safety factor K = 1,2 for important structures. Soil stiffness parameters were reduced as per K = 0,9. Soil base values were calculated as per the geological columns data within the structure footprint the soil base was simulated by linearly deforming layer. The 3D rafts analysis was done with the help of finite elements technique. The results enabled determination of cross section configuration of the rafts, internal forces in them and the required reiforcement.

During BIA construction period settlements of the main arena raft were measured. The measured settlements by the end of construction period were close to those predicted (Fig.6).

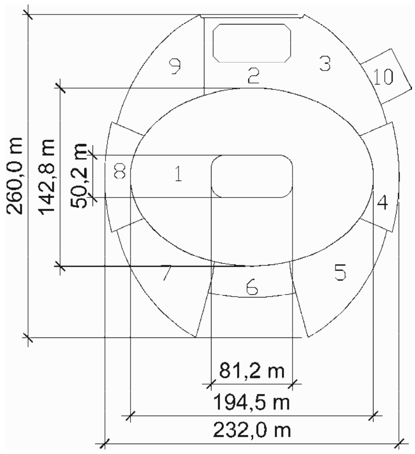


Fig. 5. Layout of Rafts of Big Ice Arena. 1. Raft of Main Arena; 2. Raft of workout arena; 3... 9 Rafts of service premises and bypass road; 10. Raft of refrigeration center.

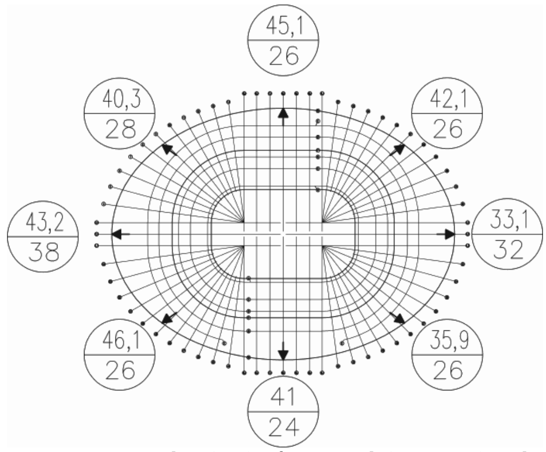


Figure 6. Mean value (mm) of measured (numerator) and analytical (denominator) settlements of arena raft footing.

3 OFFICE BUILDING OF ORGANIZING COMMITTEE

Office building of Organizing Committee of Olympic Games is located at 1200 m distance from the main facilities. The building consists of 9-storey main part and 3-storey parts, surrounding it (Fig. 7). A one-level parking lot is designed under the whole building is similar to a trifolium (one leave width is 18,7 m). The high-rise part of the building is divided into counter-seismic blocks, sitting on the solid raft. The structural design of the building consists of a framework with stiffness diaphragms in each antiseismic block. The main bearing structural elements of the building are made of cast concrete. The construction site dimensions are 120x90 m.

High-rise and low-rise sectors are divided by compensation joints. Mean design distributed load on the soil base from the 9-story component is 200 kPa, that from the 3-story is100 kPa.

The office building of the Organizing Committee of Olympic Games is located on the site that is certainly the most unfavorable as to its geotechnical conditions. Top ≈4,5 m layer composed of relatively strong clays. Underneath the top layer soft and liquid plastic clays of very low strength are lying up to 21 m depth. Some boreholes showed peat pockets at 9 to 17 m depth. At 21…23 m depth there occur coarse sands, below 23 m depth gravel-pebble muxture. Clay soils on the site feature organic content up to 10…15%.

Fig. 7. Organizing Committee Building under construction.

Table 1. Soil conditions of the Organizing Committee Building site.

Soil element	Depth, m	E, MPa	φ, deg	c, kPa
Clay	0…4,5	6	13	22
Very soft clays	4,5…21	0,7	10,6	10,3
Coarse sand	21…23	27	29	0
Mixture of gravel and pebbles	>23	53	35	0

Table 1 shows that application of spread footings is not possible, as it would result in excessive settlement. Soil improvement such as strengthening, reinforcement, replacement, etc. are not applicable because of thick layers of soft clays. Installation of drains for soil consolidation together with preloading of soil mass could not be applied due to tight project deadlines. Therefore, pile footing was the only alternative. At the stage of pile type selection there were considered prefabricated piles, bored cast piles, jet-piles, gravel piles in geosynthetic shell, etc.

The condition that complicates pile foundation design is that in order to ensure a footing seismic stability the piles shall bear the total lateral seismic load. The soil stratum capable to adequately resist to the lateral load usually occurs at over 21 m depth. In conditions of the site in question pile design bearing capacity to vertical load is times 40…60 greater that to the lateral load. In order to bear the vertical load of the 9-storey sector of the building 511 piles with 0.35x0.35 cm2 cross section are required while it requires 2030 piles to resist to lateral seismic load, i.e. times 4 as much.

Mass application of pile foundations with intermediary sand layer has started in 1960s in seismic areas of the USSR. The results of full-scale experiments demonstrated that in such foundations the lateral seismic load does not practically apply to the piles. Such foundation is recommended for practical application on sites having magnitude 7…9 seismicity. Application of pile foundation with intermediate cohesionless soil layer is not recommended by construction codes for sites with soils containing more than 10% of organic matter, collapsible soils, on karstic terrains, etc. This ban comes from possibility of collapse of loose soil and its disrupture that may result in extra deformations of the building. In order to enable application of such foundation a specific approach was required for foundation analysis and design.

Expanded pile caps together with cushion of cohesoinless soil reinforced by two layers of geosynthetics were used. Existing calculation method proposed by construction codes was developed with regard to aforementioned additions. The improved method took into account elasto-plastic properties of soils of the base; pile group effect, geometric and stiffness properties of deep footing (pile caps, reinforcement nets, etc.); stiffness parameters of foundation rafts (pile rafts); seismic conditions of construction site, etc.

The foundation design approved for implementation is shown on Fig. 8. Pile foundation below 9-th storey sector consists of 0.35x0.35 m prefabricated piles spaced over 2x2 m and for the 3-storey sector with 4x4 m square grid. The pile cap dimensions are 1,4x1,4x0,4 m. The intermediate cushion is 600 mm thick, reinforced by two layers of Fortrac 35MP geogrid. The raft thickness under 9-storey and 3-store sectors 800 and 600 мм respectively.

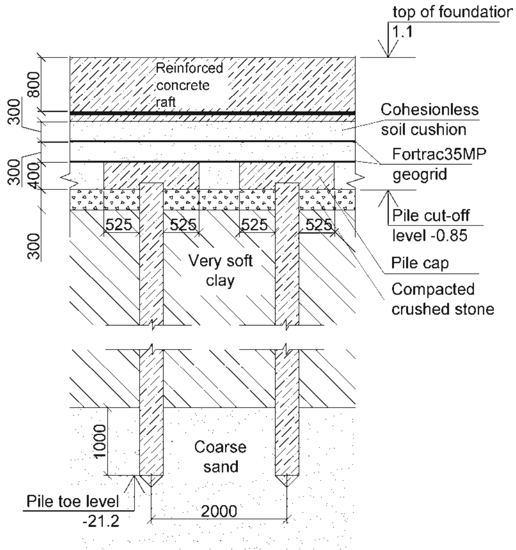


Fig. 8. Foundation cross-section for Organizing Committee Building.

The most essential factors predominant for the effectiveness of a such footing are: thickness of the intermediate layer above pile heads; pile caps overview dimensions; pile-to-pile spacing; pile cross sections; number of layers and stiffness of geogrid.

The building settlements monitoring data demonstrated that the settlement is close to analytical value and is compatible with actual standard pile footing settlements. Typical time-settlement diagrams based on measured values are shown on Fig.9.

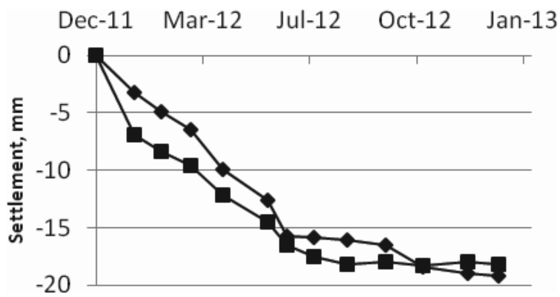


Figure 9. Time-settlement diagrams for Organizing Committee Building.

4 PLOT D1 AND PLOT 17.

Hotel complexes 3* and 4* are being constructed on plots 17 and D1.Plot D1 is located a slightly little closer to the shore.

Construction of 12 multistorey hotels (up to 8 floors) and buildings of public entertainment area is planned on plot 17. Each of the hotel building consists of two sections with dimensions of 36 x 14.9 m. Dimensions of the plot 17 is 265 x 220 m. Overview of the complex is shown in Fig. 12. Soil conditions of the site vary significantly due to its large area. The typical cross section of the site top down consists of 4 m thick fill, less frequent are peats, sludge and water-saturated silty sands, underlain at different depths (3…11 m) by gravely sands and gravel and pebble soils.

Driven concrete 30x30 cm 4-12 m long piles are applied. The length of piles depends on the depth of the bearing gravel and pebble layer, in which the pile tips are at least 0.5 m deep.

Due to variations of geological conditions within the construction site two types of footings were used in the project design (fig. 10)

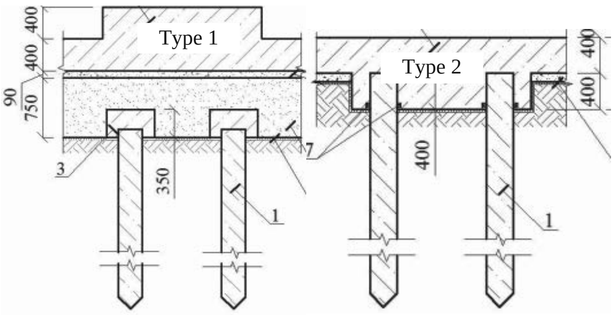


Figure 10. Foundation types for plot 17.

Type 1 (Fig. 10, left) is a concrete raft 400 mm thick with greater, up to 800 mm thickness, under bearing structures with flat bottom on pile foundation with intermediate sand and gravel layer. Presence of this layer practically excludes lateral seismic load transfer. The intermediate 0.75 m thick layer, consisting of local sand and sand-gravel soils, compacted layer by layer, is a damper, it is filled over pile heads having concrete caps. A layer of geotextile is placed between piles and under their caps separated from piles by shockproof polystyrol layer.

Type 2 (Fig. 10, right) is applied for the buildings, sitting on soil base, containing peats and peaty soils, having Young modulus of 5…6 MPa. Here a solid raft is designed of variable thickness, leveled on top, with pile heads fixed in the raft. The piles, bearing lateral seismic loads, have strong reinforcement in accordance with construction codes.

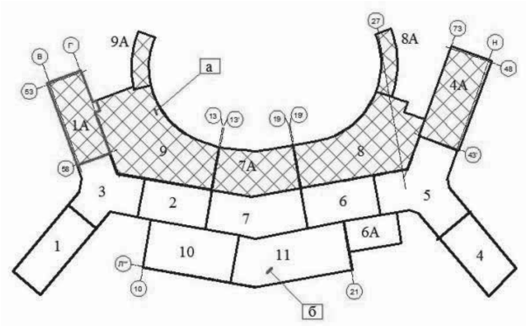
The pile field is designed to withstand the main and the special (seismic) combination of loads.. The design load, applied to the piles, is 750 kN for the main combination and 1000 kN for the special one. The piles bearing capacity of 1000 kN was proved by static load tests. The design lateral load on the piles does not exceed 35 kN for pile-raft rigid fixation.

Hotel, apartments and support services at plot D1 are located in the single building, separated by settlement and anti-seismic joints into sections (Fig. 11). Overall dimensions of the building are 150x264m.

Soil conditions of the plot D1 vary significantly within the building footprint, which determined the choice of different types of foundations within the same building.

On the part of the site (blocks 1-7, 10, 11 on figure 11), located close to the shore, surface part of the geologic section consists of large thick deposits of sand and gravel, underlain by gravel-pebble soils. For these conditions, the foundation is designed as a cast reinforced concrete raft with thickness of 400 mm. Under heavily loaded walls and columns 800 mm thick upward ribs are provided to increase stiffness of raft.

A further from the shore (Blocks 1A, 4A, 7A, 8, 8A and 9 in Figure 11) upper part of geological section consist of weak man-made soil, covered by fill produced during engineering preparation of the construction site. Due to low strength of these soils, they can not be used as the foundation base. Therefore, to minimize the differential settlements of adjoining blocks, pile



foundation with intermediate cohesionless soil cushion were designed similar to the one designed at plot 17 (Fig. 10 left).

Figure 11. Foundation layout for building on site D1. Hatched areas represent pile foundation, blank areas – raft foundation.

5 GEOTECHNICAL FEATURES OF UNDERGROUND PIPELINES DESIGN.

In order to ensure operation of the main Olympic facilities on Imeretin lowland terrain it was necessary to build a multi-kilometer long and dense network of various underground service lines for various purposes (heat and water lines, sewage and rainwater systems), of various liquid transportation principles (non-pressurized and pressurized), made of various pipeline materials (steel, polyethelyne, polypropelene), of various pipe diameters (250…1580 mm), with and without protection.

The main issue in foundation design for service lines is the account of potential considerable differential settlements of soft consolidating soils and, as a consequence, those of pipelines, caused by fill loading of the terrain. According calculation results the settlements of 5…20 m thick soft soils could be up to 0.7 m and could develop for several months or years even if special geotechnical techniques are applied to accelerate soil consolidation (sand and geosynthetic drains, temporary loading fill, jet stabilization, etc.). Application of other techniques of soil stabilization (stone columns, soil reinforcement, jet stabilization, etc.) was neither possible for financial and tight schedule reasons.

In view of the project of such scale the NIIOSP specialists had to develop special recommendations for service lines that outlined admissible deformations, missing in Russian construction codes (see Table 2). The assumed approach was based on limit state design analyses. This enabled selection of effective foundations types for the whole spectrum of numerous waterlines. Thereafter (Fig. 13) some service lines were designed to sit on driven concrete piles, other ones on cast concrete strip footing on natural or on improved ground, made by complete or partial replacement of soft laguna deposits by

Table 2. Ultimate admissable deformations of service lines.

Verification analysis type	Service lines			
	Pressure lines		Gravity lines	
	Water supply line (polyethylene)	Hot water line (steel)	Domestic sewage line (polypropylene)	Runoff water line (polypropylene)
Pipe line strength check	$r \geq r_{min} = 50$ м	$r \geq r_{min} = 400$ м	-	-
Pipeline gravity flow check	-	-	$i \geq i_{min} = 2{,}5 \cdot 10^{-3}$	$i \geq i_{min} = 0{,}8 \cdot 10^{-3}$
Pipeline plumbing check	-	-	$\varphi_{max} \leq 1^0$	$\varphi_{max} \leq 1^0$
Concrete duct crack resistance check	-	$r \geq r_{min} = 16{,}7$ км	-	-

Note. r and r_{min} are design and minimally admissible radius of pipeline curvature; i and i_{min} are design and minimally admissible pipeline slopes; φ and φ_{max} are design and maximally allowable angle of rotation in pipeline joints.

gravel and pebble fill.

Figure. 12. Overview of plot 17.

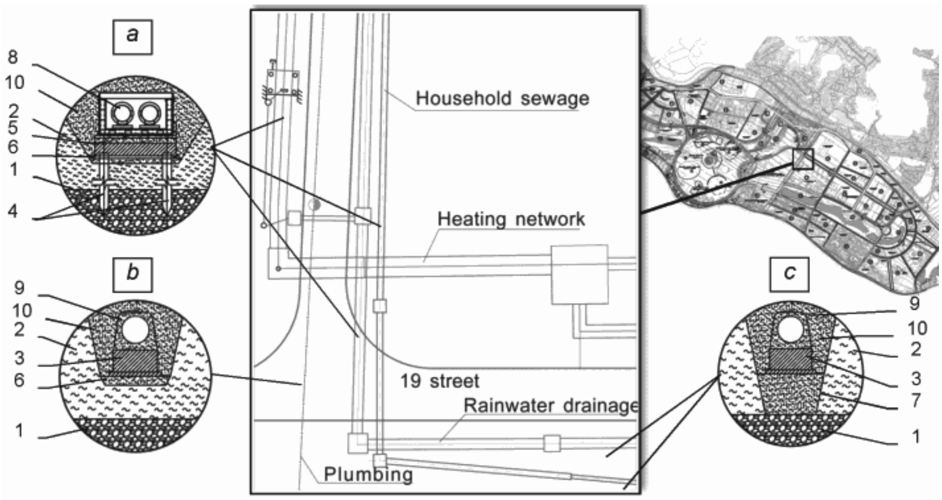


FIGURE. 13. Design solutions for foundations of underground water lines within Imeretin lowland terrain: a – driven pile footing; b – concrete strip footing on natural soil; c – concrete strip footing on replaced soil (replacement of soft soils by sand and gravel mixture). (1 – sand and gravel soils; 2 – soft clay soils; 3 – concrete strip footing; 4 – concrete driven pile; 5 – concrete raft; 6 – sand and gravel fill; 7 – replacement of soils with sand and gravel fill; 8 – pipeline in protective duct; 9 – pipeline wrapped around with geotexticle in sand fill; 10 – sand backfill).

6 CONCLUSIONS

Imeretin lowland, where main Olympic facilities are erected, features complicated geotechnical conditions, presence of thick soft clay deposits, high underground water level, and high seismicity of the area.

The above factors as well as the necessity of construction within tight deadlines of many sports facilities, including unique buildings and structures, made the designing engineers to face complicated challenges, which they finally coped with thanks to the accumulated experience of the national geotechnical community as well as to application of new approaches and effective design solutions.