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LARGE BORED PILES FOR THE NEW DANUBIAN BRIDGES IN ROMANIA
DE GROS PIEUX FORES POUR LES NOUVEAUX PONTS DU DANUBE

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SYNOPSIS
After the attempt made by the famous Roman architect Apollodor of Damascus,who built in 103-105 a.C. a bridge at Turnu - Severin,which did not resist in time,Danube had to wait almost 19 centuries to see again permanent passes over its lower course. These were the bridges built at the end of the 19-th century in Romania,over the Borcea arm of the Danube,at Fetesti,and over the Danube itself,at Cernavoda,under the direction of Romanian civil engineer and professor Anghel Saligny.Provided with only one railway,these bridges could not accomodate the traffic of present days.80 years after the inauguration of Saligny's bridges,it was decided to build new ones,close to the existing but able to support two railways and a four-lane road.The heavy loads as well as the difficult soil conditions have imposed the use of large diameter bored piles.Almost 2,000 such piles have been incorporated in the 8 foundations of the main bridges and in the 87 foundations of the viaducts.Benoto piles,with recoverable casing,of 1.08 m in diameter,have been used predominantly for the viaducts,while the piles for the foundations of the main bridges were exclusively piles with steel casing,1.96 m in diameter,left in place.A complex program of field tests on piles was set up and is described.An outstanding test was performed on a 1.96 m diameter pile,on the left bank of the Borcea arm,which was loaded directly by placing lest on a reinforced concrete cap up to a total load of 40,080 kN,probably the highest ever reached on this type of loading scheme.

SHORT GEOGRAPHICAL AND HYSTORICAL OUTLINE

Romania is located in the South-East of the central part of Europe.With a surface of 237,500 sqkm and a population of more than 23 millions,Romania is a country of medium size, crossed by the parallel of 45^0 and cut in almost two equal parts by the meridian of 25^0.The territory of Romania is related to the presence of three major geographical elements: the chain of Carpathians Mountains;the lower course of Danube,including its mouth forming a wonderful delta;the Western coast of the Black Sea.

From the entire length of the Danube- 2,060 km- more than one-third,precisely 1,075 km,practically all the lower course, are on Romanian territory,either as a natural border with Yugoslavia,Bulgaria and Ukraine or in the interior of the country.One can realize that bridges over Danube are of vital importance for this country.

The oldest known bridge in the lower course of the Danube, which unfortunately did not survive,was the bridge of more than 1,200 m length built in 103-105 a.C. by the famous Roman architect Apollódor of Damascus near the town called today Turnu-Severin.The bridge was commissioned to Apollodor by the emperor Trajan who,after his second and victorious war against Dacia,realized that in order to keep his conquest a fixed bridge was mandatory.As mentioned,the bridge did not resist in time.Its ruins remind the Roman origin of the Romanian people.

The second permanent bridge in the area concerned was built almost 19 centuries later,between 1890 and 1895.There were actually three bridges,over the arm of the Danube called Borcea,over a lake,Ezer,which was eventually filled,and over the Danube itself.They cumulated by the time of their erection several records,as such:
- a world record: with the total length of over 3 km,it was the largest pass of this kind ;
- an European record: the central span of 190 m of the bridge over Danube,was the largest in Europe.

The foundations of the bridges were pneumatic caisson made

Fig. 1 Map of Romania with a mark for the location of the two bridges

of concrete and natural stone blocks on a steel skeleton,covered by a steel sheet 8 mm thick.The caissons were founded at 25...27 m below the level of lowest waters,with an allowable pressure on the base of 10 daN/sqcm.The designer and the chief engineer of the construction of the bridge was the Romanian engineer Anghel Saligny,Professor at the National School for Roads and Bridges from Bucharest,the most venerated figure of the Romanian history of civil engineering.

The bridges built by Anghel Saligny between the town of Fetesti,near the Borcea arm,and the town of Cernavoda,near the Danube,provided with only one railway,could not accomodate more than 83 pairs of trains per day in 1974,as compared to 145 pairs of trains per day,the capacity of the line which was doubled in 1968-1970 on the land between the bridges.The need for a new railway bridge was obvious.As for the cars,the sole existing bridge,at Giurgeni-Vadul Oii (steel bridge completed in 1970) along with several crossing points by boats, were unable to take the traffic. As a result, in 1975, the Romanian Ministry of Transportation decided to build two more bridges for double railways lines, and also for a 4-lane road, thus creating a link between Bucharest and Constantza 42 km shorter than the existing one. As one can see in the fig.1, the two bridges and the 14 km of road connecting them through the island, make part of a motorway Bucharest-Constantza. This motorway, whose construction started in 1992, is the first to be built from an ambitious program of more than 3,000 km of motorways, to be accomplished in Romania in the next decades.

GENERAL DATA ON THE BRIDGES

The new bridge over the Borcea arm at Fetesti was placed downstream, with a slight obliquity toward the existing one, at about 40...100 m distance. The bridge has a total length of 970 m, made of:

- viaduct of the left bank, 3 spans :49.50+50.0+49.50 m
- main bridge, 3 spans of 140 m each
- viaduct of the right bank, 8 spans :49.50+2 x 50.0 + 49.50+2 x 50.0+49.50 m

SOIL CONDITIONS

Borcea bridge. Geological profile (fig.3) comprises a sequence of layers of sand, silty or clayey sand, with lenses of small gravel with sand, up to a depth of about 40 m, followed by a layer of marlish clay, stiff and very stiff. At a depth of about 47 m is a layer of marlish limestone, compact, with a thickness of 3.0-3.6 m. Unconfined compression tests on sample 83 mm in diameter from this rock gave a strength ranging between 190 and 230 daN/sqcm. The limestone is followed by another layer of marlish clay, 7-10 m thick. The dotted line shows the situation in 1890.

Danube bridge. Geological profile (fig.4) puts into evidence alluvium deposits of fine and medium uniform sands, with lenses of round gravels, in the major streambed. In some borings, thin layers, under 2.0 m thick, of cohesive soils, also were found. Sands are predominant in the minor streambed, followed by clayey marls and calcareous marls and by tuffaceous limestone which represents the bedrock at a depth of -25.0 m below sea level. The width of the river in the bridge zone is about 450 m, the speed of water is about 2.9 km/h. Comparative studies of the batimetric measurements showed that in

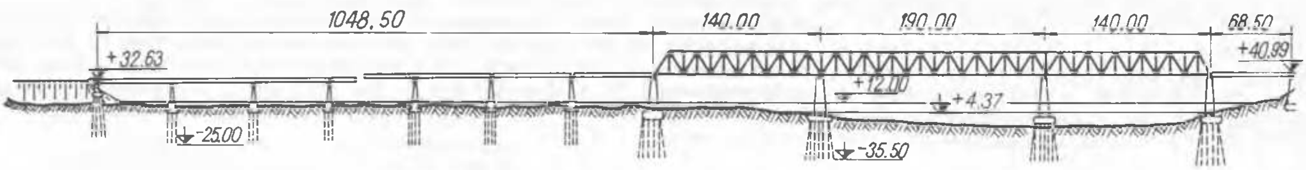

Fig. 2 General lay - out of the Danube bridge at Cernavoda

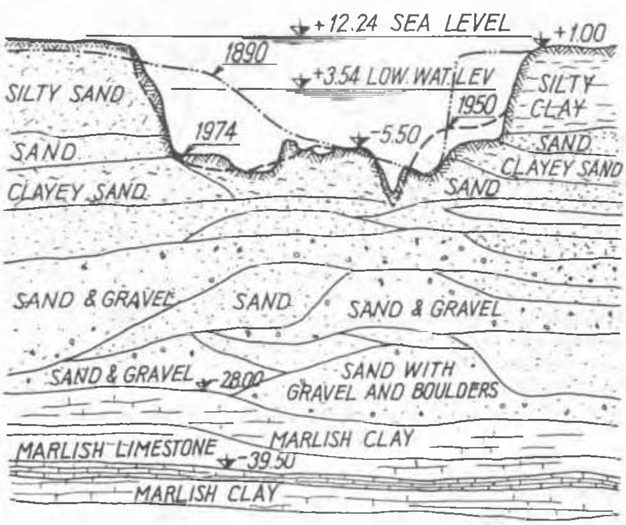

Fig. 3 Borcea bridge - geological profile

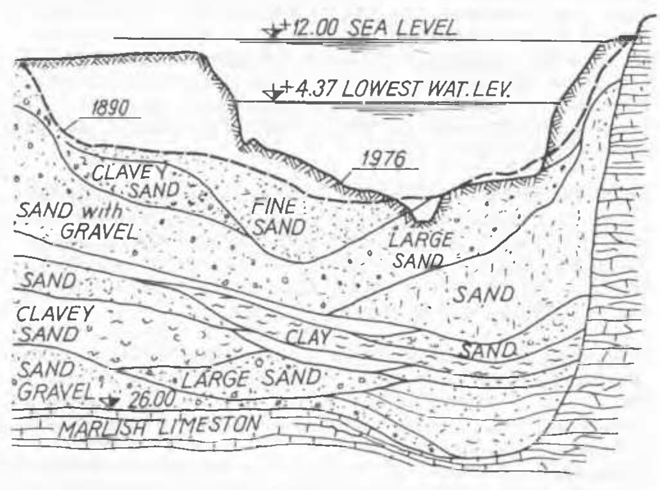

Fig. 4 Danube bridge - geological profile

The new bridge over Danube at Cernavoda was placed upstream, at a distance between 30 and 80 from the existing bridge. The total length of the Cernavoda bridge is over 1,700 m, from which :

- viaduct on the left bank, 17 spans totalling 1,098.5 m
- main bridge, 3 spans : 140 + 190 + 140 m
- one span linking with the right bank :68.50 m

Fig. 2 shows a general lay-out of the bridge.

85 years (1890 - 1975) the width of the Borcea arm increased by 100 m, while the old Danube reduced its width at Cernavoda by the same amount. For the both bridges, the total erosion at high waters was estimated to be 8.0 m in the major streambed and 16.0 m in the minor streambed.

FOUNDATION SOLUTIONS

Since on both locations,in the minor streambed appeared layers of low bearing capacity 15 to 20 m in thickness, namely fine,silty and clayey sands,the only efficient solutions for viaducts seemed to be that on large diameter piles, lowered to the high bearing layers of sand with gravel.This solution was imposed not only by the bearing capacity criterion but also by the deformation criterion,having in mind that the upperstructure for the viaducts are statically indeterminate continuous beams with 3 or 4 spans.A differentitation was made based on the elevation of piers.

For piers of low elevation,between 8 and 20 m,at which the upperstructure had in general mobile bearings,Benoto bored piles with recoverable casing of 1.08 m diameter,20-24 m in length,were used.

For piers at high elevation,or where the upperstructure had fixed bearings,bored piles of 1.50 or 1.74 m diameter were used.

For the main bridges,in the minor streambed,end bearing piles,1.96 m in diameter,lowered to penetrate the layer of marlish limestone,at Fetesti,and the one of tuffaceous limestone,at Cernavoda,were employed.

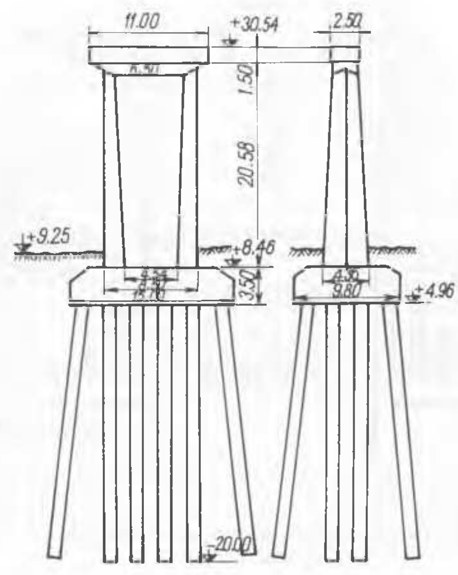

Fig. 5 Typical foundation for a viaduct

The total volume of pile work was :
- for the main bridges,in the minor streambed:213 piles, 1.96 m in diameter,placed in 8 foundations ;
- for the viaducts,in the major streambed:1700 piles,most of them of 1.08 m in diameter,placed in 87 foundations.

Figs. 5 and 6 show typical arrangements of piles in a viaduct foundation and in a main bridge foundation.

CONSTRUCTION METHODS FOR PILES AND FOUNDATIONS

Except Benoto piles,all the other piles were bored piles with left in place casing.

The construction phases for the 1.96 m diameter piles used in the foundation of the main bridges were the following :

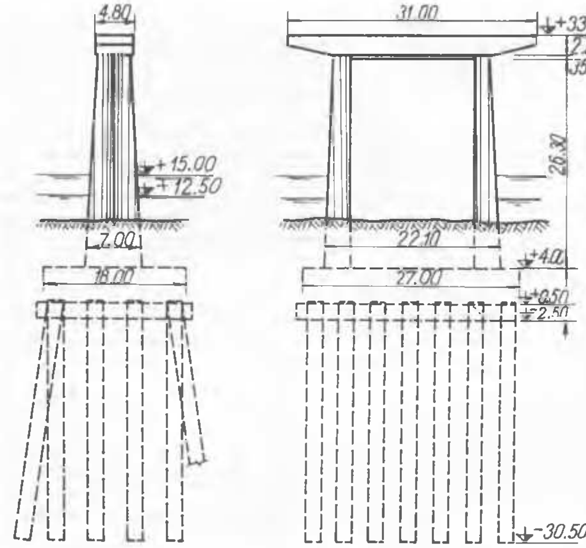

Fig. 6 Typical foundation for a main bridge

- on the top of the casing a pair of vibrators was placed by the intermediary of a cap and was put to work in order to lower by vibration the tube ;
- after the first section of the tube ceased to penetrate,as a result of the high friction developed between the soil and the casing both inside and outside the tube,the vibrator was removed in order to allow the boring of the soil plugged inside ;
- new sections of the casing were added by welding,as phases of vibration and boring were alternating,until the final level,established in the project,was reached ;
- the rebar cage was lowered in the casing ;
- the concrete was placed using the Contractor method.

All piles,regardless theirs diameter and type,were equipped in order to allow the grouting at the base.Water-cement grout was used and the grouting started after the whole group of piles under a foundation was put in place.

Various procedures have been used for the construction of the reinforced concrete cap connecting the piles.They differentiated depending on the depth of the water in the location of each pier.It is worthwhile to describe here the method used for piers at high waters,in the minor streambed,at which the main feature of the construction of the concrete cap connecting the piles and supporting the pier was the use of a so-called caisson-cap.Three such caisson-caps,made at the Galatzi shipyard and transported by floating,like boats, on the Danube,having a surface of about 500sqm and a height of 3 m,were used.Openings were previewed at the bottom of these boxes for guiding eventually the 1.96 m diameter casings.During the transportation,the openings were tightly closed,to allow floating.

The first stage of the construction of the concrete cap,after the towing of the caisson from the shipyard to the site,was to place the caisson in the mouth of a DeLong platform anchored in place (fig.7).In order to be lowered at the design level (14-16 m under the level of highest waters)the caisson was suspended in 4 steel columns,in fact 4 piles of the future foundation,descended to the bearing layer and fully or partly concreted (fig.8).By this way,the caissons remained connected to the 4 vertical piles without being linked any more to the floating platform and influenced by the variations of the water level.On the internal steel structure of the caissons and on its contour a supporting frame and a sheet piles row was placed.The height of the sheet piles was chosen in such

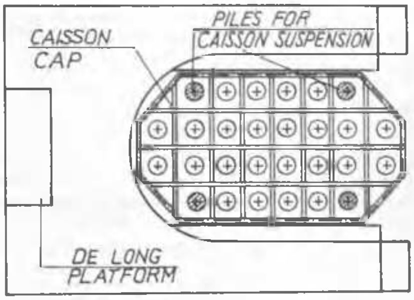

Fig. 7 The caisson - cap in the mouth of the DeLong platform

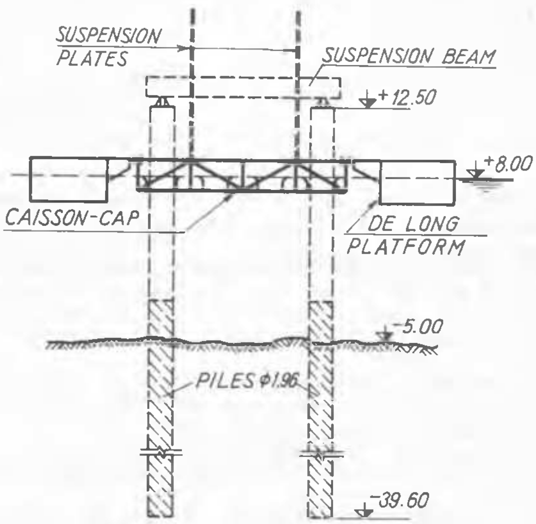

Fig. 8 Vertical section through the caisson - cap and DeLong platform

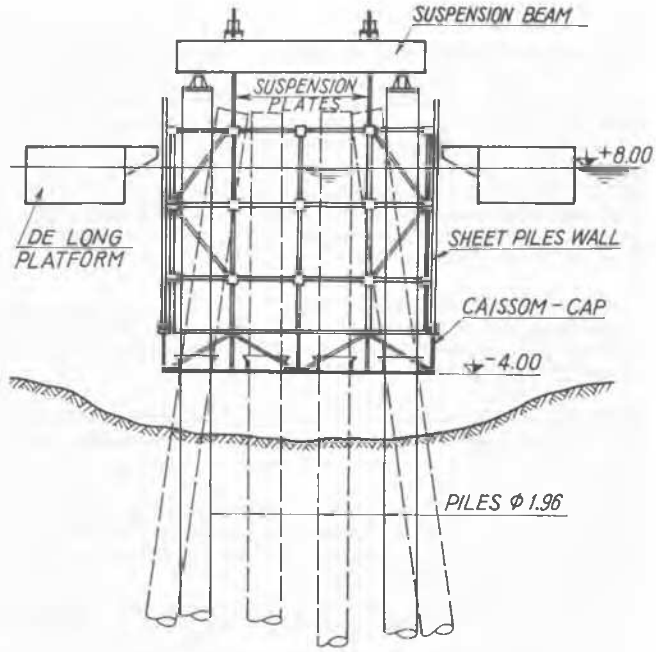

Fig. 9 The caisson - cap and the sheet pile wall lowered at the final level

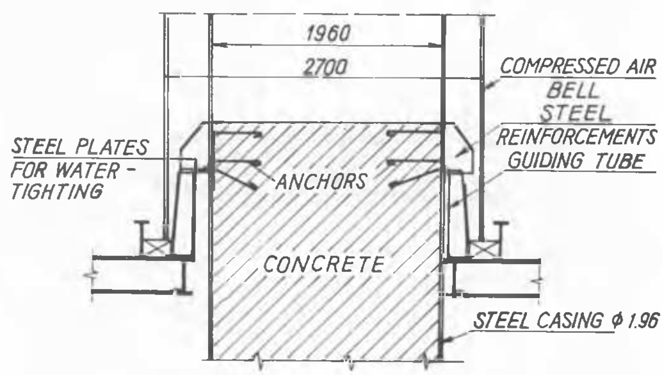

Fig. 10 Watertighting of the pile using the compressed air lock

a way that,after lowering the assembly "sheet piles + + caisson ",the upper part of the sheet pile to remain above the highest water level.The whole construction,weighting about 900 tons,suspended in 4 points,was lowered to the design level (fig.9).Since the openings of the bottom of the caisson were free,the whole assembly was flooded.The placement of the rest of piles of the foundation followed.Piles were welded in sections of 6 to 12 m.Each vibration phase lasted between 10 and 15 minutes,then the vibrator was removed and the boring of the soil plugged inside was done. Concrete in the pile was placed under water,after cleaning the stuff at the bottom by means of an air - lift.For the watertighting of the caisson,steel plates had to be placed around the casing of the piles (fig.10). This work was done under water in a steel bell made of a pressed air lock and a 14 m in height and 2.10 m in diameter (2.70 m in the lower 2 m) tube.Air pressure of 1.2-1.7 bars was used.After watertighting all the piles,the water was pumped and the mud 3-4 m in height,at the bottom of the caisson,was removed.The construction in dry of the reinforced concrete cap connecting the piles could then proceed,followed by the erection of concrete piers, protected by 50 cm thick granite blocks. Thus, the infrastructure was completed.

FIELD TESTS ON PILES

Taking into account the great number of piles and the construction methods proposed by the designer and accepted by the contractor,and also the provisions of the Romanian code for bored piles which require that for important jobs and in difficult soil conditions the determination of the bearing capacity of piles to be based on loading tests,a complex program of tests and research was set up.A total number of 11 piles were tested axially, from which 3 have been tested outside the foundations (test piles properly named)and the 8 others were tested on the foundation site and remained in the foundation.For this last category,a maximum load up to 1.5 times the exploitation load was accepted.The three test piles were placed on the left bank of the Borcea arm.In fact,most of the efforts of the experimental program concentrated on the Borcea bridge,since it was the one to start with and all the results and informations to be obtained, either from the stand point of the pile behaviour under loads or from that of the construction techniques, could have been beneficial for the works to follow.

The major test was to be performed on a 1.96 m diameter pile. Since it was anticipated to reach a maximum axial load of 45,000 kN, the only feasible solution appeared to be the load applied directly on a reinforced concrete cap 10 x 10 m, 3.0 m in height, built on the top of the test pile. The same solution was applied also to two Benoto piles, for which the caps had 7.5 x 7.5 m and 2.5 m in height.

The three test piles are shown in the fig. 11.

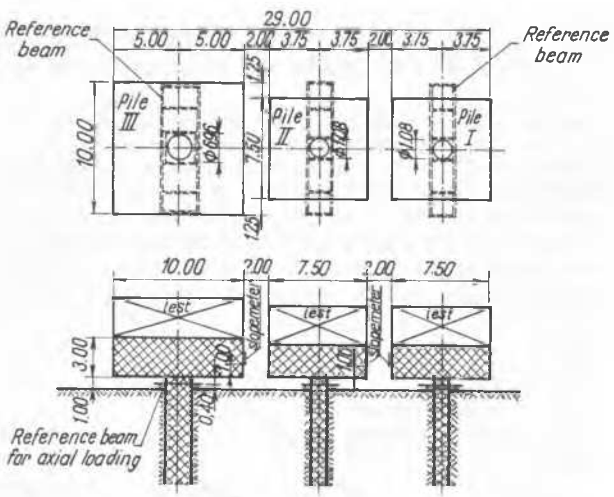

Fig. 11 The three test piles on the left bank of the Borcea arm

The lest to be placed on the concrete cap was made of stacks of rails, weighting 23,000 kN and of steel bars weighting 8,000 kN. Loading was made in steps, each step of about 200 tons, up to the maximum allowed by the conditions of stability of the lest, namely 40,000 kN, including 7,500 kN the own weight of the cap, without reaching thus the ultimate load of the pile.

The load-settlement diagram of the Borcea 1.96 m diameter pile is shown in fig. 12. As one can see, up to the seventh load stage (20,000 kN) the settlement increased almost linerly with the load, reaching 8.08 mm. After this load, the slope of the load-settlement diagram slightly changed, as a result of the mobilization of the skin friction. The final settlement was of only 20.6 mm.

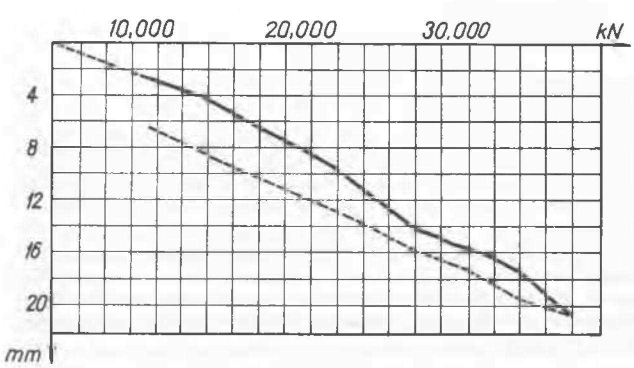

Fig. 12 Load - settlement diagram of the 1.96 m diameter pile Borcea

The two Benoto test piles on the Borcea site were also loaded directly. The first load was represented by the weight of the cap :4,000 kN. The concrete of the cap was placed in contact with the ground. A manual excavation corresponding roughly to 50 % of the contact area was then performed. The rest of the contact was cut by a steel cable towed by a tractor. Then the load on the cap was applied in increments of 1,000 - 1,200 kN. Under the final load of 13,000 kN, the settlement reached 90 mm. The second Benoto pile with direct loading on the cap behave in a similar way: for a load of 15.195 kN the settlement was 10,9 mm.

As mentioned before, the 8 other piles were tested on the site of the foundation in which they were incorporated eventually. The load was applied through hydraulic jacks, the reaction being provided either by platforms supported by the ground and lested to insure the counter-weight or by platforms connected to 2 or 4 anchoring piles.

The results of the tests on axially loaded piles are summarized in the tab. 1. Some additional comments on several results seem necessary. Test No. 6, on a steel casing 1.50 m in diameter and 30 m in length, lowered by vibration and then left unconcreted, had as purpose to put into evidence the bearing capacity due solely to skin friction. An average limit value of 37 kN/sqm for the unit skin friction was thus recorded. Two Benoto piles of equal diameter and length and in similar soil conditions(tests No.5 and 8) exhibited significant differences in deformations under load due to the fact that one had the base grouted while the other had not. Test No. 7 on a 1.74 m diameter pile made of a vibrated reinforced concrete casing, lowered at a depth of 24 m, had to be stopped at the load of 10,000 kN because of the failure of a bolted joint of one of the anchoring piles.

Tab. 1 Tests on axially loaded piles

No	Site	Type of pile	Diam. m / Length m	Load/settlement KN/mm a	b	c	final
1	Borcea Test 1	Vibrated steel casing Ungrouted	1.96 / 51.50	6000 / 2.20	13.500 / 5.00	25.000 / 11.40	40.000 / 20.40
2	Borcea Test 2	BENOTO Ungrouted	1.08 / 25.00	4.800 / 18.70	6.000 / 21.17	10.000 / 42.92	13.000 / 90 79
3	Borcea Test 3	BENOTO Ungrouted	1.08 / 25.00	4.630 / 0.83	6.530 / 4.64	8.840 / 12.54	15.190 / 109.27
4	Borcea viaduct	BENOTO Grouted	1.08 / 20.00	2.000 / 1.26	3.200 / 2.14	4.000 / 3.71	5.200 / 4.59
5	Danube viaduct pier 1	BENOTO Ungrouted	1.08 / 25.00	2250 / 3.55	3.150 / 7.08	3.650 / 11.74	4.950 / 44.07
6	Danube viaduct pier 2	Vibrated steel casing Unconcreted	1.50 / 30.00	3.600 / 5.16	4.800 / 12.75	5.250 / 18.26	5.250 / 18.26
7	Danube viaduct pier 5	Vibrated r.c. casing Grouted	1.74 / 24.00	6.000 / 1.90	8.000 / 4.12	10.000 / 6.85	10.000 / 6.85
8	Danube viaduct pier 9	BENOTO Grouted	1.08 / 25.00	2.800 / 2.07	3.600 / 4.07	4.800 / 8.03	6.000 / 15.86
9	Danube viaduct pier 14 I	BENOTO Ungrouted	1.50 / 25.00	3.200 / 2.60	4.500 / 9.60	6.000 / 26.00	8.500 / 36.00
10	Danube viaduct pier 14 II	BENOTO Grouted	1 50 / 24.00	2.200 / 2.57	4.400 / 6.83	6.00 / 15.43	7.200 / 28.20
11	Danube bridge River pier	Vibrated steel casing Grouted	1.96 / 28.00	6.570 / 3.41	14.370 / 8.55	21.875 / 16.20	21.875 / 16.20

The last test of the whole program was carried out on a 1.96 m diameter pile,in one of the foundations of the Danube bridge at Cernavoda. A reaction platform with two steel frames and four anchoring piles was used. Five hydraulic jacks,of 5,000 kN capacity each,have been used to apply the load. A special problem was put by the extension of the pile from the level of the cap,where the concreting was stopped, to the level of the testing platform,in total 15.5 m. A temporary extension was created by introducing in the main casing of 1.96 m diameter a new concentrical tube of 1.50 m diameter,with concrete on 2.0 m at the lower part and the annular space between the tubes concreted on its entire length. The load was applied in increments of 1,000 kN,up to 21,875 kN,when a settlement of 16.28 mm was recorded.

This was an instrumented pile. Both electroresistive and vibrating wire transducers were used in order to asses strains and stresses at various locations along the pile shaft. Electroresistive transducers have been of the Mustran type and were manufactured at the shop of the Bucharest Research Institute for Transportation using for the electrical part materials provided by the University of Texas at Austin in the frame of a cooperative research project. Vibrating wire transducers have been of Telemac type. Both Mustran and Telemac transducers have been placed between the bars of the rebar cage at a minimum distance of 120 mm from the cage,to the interior,in order to obtain a good embedment in the concrete.

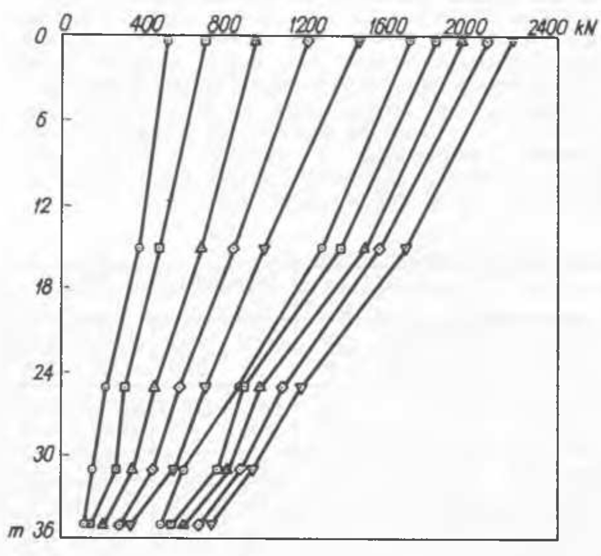

Fig. 13 Load - distribution curves for instrumented pile

The protection of cables for all transducers was assured by steel tubes placed between the bars of the rebar cage and extended to the upper part of the pile tube. Despite protective measures,some of the transducers failed. Nevertheless,the instrumentation led to several consistent results which are presented in fig. 13, 14 and 15.

In general,the behaviour of the 1.96 m diameter pile for the Danube bridge has a striking ressemblence with the one of the 1.96 m diameter pile from the Borcea bridge. The load-settlement relationship was linear up to a load of 11,875 kN under which the settlement was 6.31 mm. Then the slope of the curve changed a little,the final settlement under a load of 21,875 kN being 16.28 mm.

The field tests program included also the horizontal loading of the 1.96 m diameter pile on the left bank of the Borcea

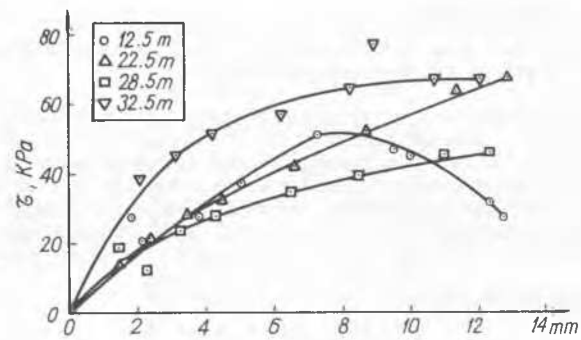

Fig. 14 Load - transfer curves for instrumented pile

arm against a frame made by connecting the caps of the two 1.08 m diameter Benoto piles. Under the maximum applied load of 1,755 kN the lateral deflection of the pile was of 16.57 mm.

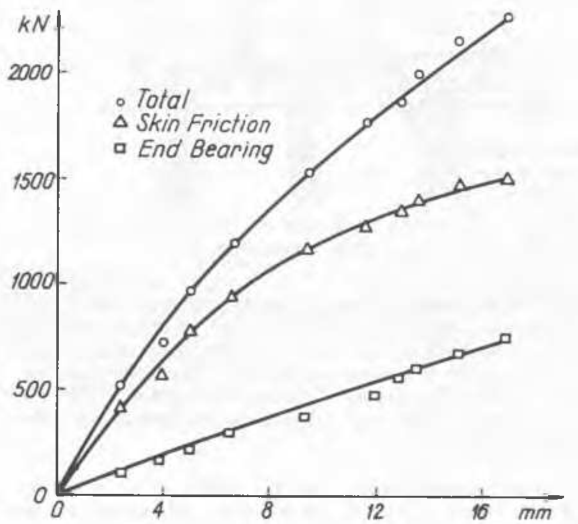

Fig. 15 End bearing vs tip movement and skin friction vs tip movement for the instrumented pile

CONCLUSIONS

A major civil engineering work has been recently completed in Romania : the new Danubian bridges. Deep foundation elements of high bearing capacity have been used in great number -1,913- to solve the difficult foundation problems. The complex research program on the site gave the opportunity of a completely unusual load test in which a lest applied on a large cap of a pile 1.96 m in diameter,led to a total axial load of 40,080 kN which represents,at the best knowledge of the authors,the highest load ever reached by this manner on a test of piles.