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The Engineering of Braga Municipal Stadium

The New Braga Municipal Stadium

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Introduction

The site was a hill with a very good granite quary on its top and the Client wanted a 30.000 seat Stadium. The view of the valley was beautiful: Eduardo Souto de Moura imagined one stadium with only two stands - as in a Greek Theater, one would be carved in the rock; the other one would stand up from the ground. A more conventional option, with four stands, had also been developed. Accepting the extra cost, the Client opted for our preferred option.

There was little geotechnical information available but the visible rock on the quary gave us confidence to explore the route. The question was to know if we could trust that the rock was there in depth, and how would it stand in near vertical 50m high slopes. How much time would it take to excavate it and how much would it cost? We were in the beginning of 2000 and the Stadium should be finished by the end of 2003.

Preliminary information collected in the available resources and a preliminary geotechnical survey released our main worries: we would find the granite all way long but we would have to adapt the slopes to the level and orientation of the slipping plans of the rock, still to be determined. Time wouldn't be a problem if the excavation could begin and the cost of the excavation could be significantly reduced by selling the excavated material. In August 2000 the excavation contract began.

By that time, based on a more detailed geotechnical survey, we already knew that the orientation of the fractures was unfavourable for the big hill and a slope stabilization contract was also put in place. The methods of excavation and the size of the blocks they would produce were the main conditions for the slopes to be obtained. Ideally, the cuts should be vertical. With the general layout as a starting point, and making allowances to face possible problems during excavation, the geometry of the big "hole" was established and the methodology and sequences of operation were specified. The contract went on on a permanent assistance basis of the design team to analyze and deal with what was being found. The main unforeseen situation that had to be handled was the appearance of a layer of clay that could not be detected by the geotechnical survey. Affecting the slope of the excavation and obliging to use complicated systems of soil stabilisation, the solution was to "move" the footprint of the building forward by more or less 20 m in order to assure that the slope would have a sufficient layer of rock in its outer face.

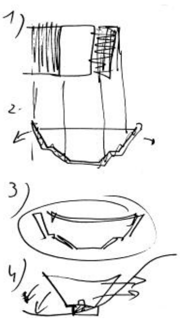
The roof was the second big challenge for the team. The roof should go along with the idea of integrating the Stadium in the environment. It should be as light and clean as possible. Arches, trusses, poles, cables and membranes wouldn't fit in the concept.

A suspended roof such as Siza's / ARUP/ STA'S Portuguese Pavilion in EXPO 98 came up as the natural solution. The rock was there to anchor the cables and the reaction of the roof in the cantilevered stand would "help" stabilising it. The doubt was the dynamic behaviour of a 220m span roof and the fact that the roof would have to be built 50m high (the Portuguese Pavilion is 67.5 m span and had been built with a total propping system from the ground!)

Research on similar structures and preliminary calculations showed the feasibility of the solution and that an appropriate geometry and slab weight could lead to a desirable balance of moments in the foundation for permanent combinations of loads.

During the development of the design, the need to change the slope of the cantilever to suit the brief and sight angles moved us away from the original goal of balancing the moments on the foundation.

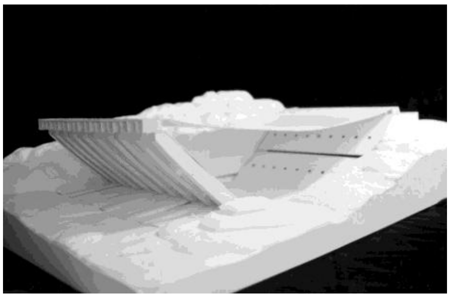
A structure of parallel blades would provide the required stiffness for the stand and would allow to fit all the stairs, concourses, bars, etc, in the middle.



Acting on the safe side, we were committed to the idea of a continuous roof. This solution, however, could not allow enough light for the pitch. The division of the roof in two had then to be faced and tested.

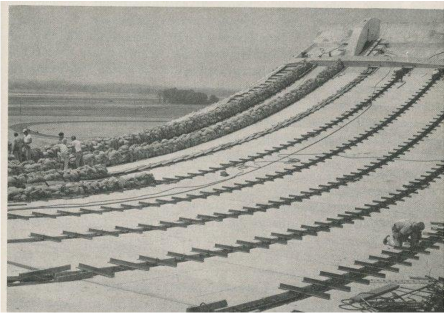
Studies were performed using a static approach of the wind and a pressure coefficient distribution was established using bibliography and the weight of the roof was initially chosen to counter the uplift forces of the wind.

The first dynamic analysis was performed in the Engineering School of the Oporto University (FEUP). A three-dimensional finite element model was used to obtain the mode vibration shapes and their frequencies. The structural response of the roof to the wind action at the ultimate limit state was also calculated.



These results showed that the solution with two separate roofs was possible but confirmed the need to develop the analysis of the dynamic interaction between the roof and the wind.

To validate the solution of the roof other issues had to be addressed: would a two stand stadium be comfortable in windy days? How would the shadow of the cables affect television transmissions? Would the ventilation and sun exposure of the pitch be enough?



The calculation of the main forces on the stands and on the foundations also showed the feasibility of the solution. Buildability was studied and a precast plank slab proved to be a feasible solution for the construction of the roof (Dulles airport in Washington had been built that way 30 years before). Cost estimates revealed that it could fit the budget.

The concept was then fixed and detail design began.

Architecture and Engineering

The program was new to the whole team. With no preconceived ideas, we started from scratch. The architect studied the functional and spatial requirements of the Stadium and we visited together several Stadiums recently built in Europe, analysing and questioning their options.

In Souto de Moura´s Architecture the technical needs of the construction rule the development of the design. Beyond what results from the definition of the spaces, aesthetics results of an intense, demanding and stimulating dialogue between the architecture and the engineering, whereby the search for solutions only ends when both disciplines are satisfied. Clear and rigorous criteria are agreed to discipline the solutions for the technical needs of the building. Technical solutions must respect them.

Precision, lightness and formal simplicity are the aims to pursue.

The result must be simple in form and in detail. But simplicity is only achieved through a gradual and continuous process of successive modifications that often bring up solutions that are quite different from the original ideas. Everybody was open to question previous options and, during the process, time often judged if the chosen solutions were appropriate, from the structural and architectural points of view, together. In this project "forced" solutions always ended up being changed in the course of time.

Architects and Engineers worked together to achieve a common goal, which was not viewed as the exclusive territory of one or the other.

The original idea to "fit" the Stadium into the quarry, with only two stands, started a process in which the solutions encountered were the natural sequence of confirming and consolidating ideas, the viability of which was not given at the start. The initial choice of the road to follow was based more on sensibility and instinct than on known results. The essential process of research and confirmation followed, in which the criteria for accepting solutions was based on rigorous cost/benefit analyses (functional, technical, economical and aesthetical).

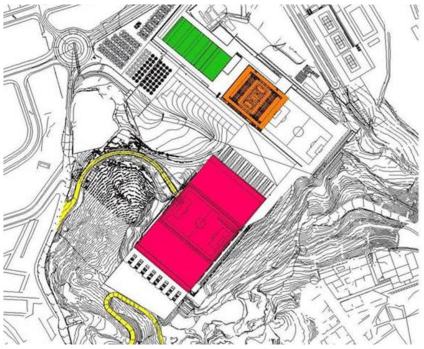
In this process we were aware of the risk that arises from constantly pushing back the limits, and controlled it through an intensive research methodology. Risk assessments, redundancies, independent teams studying the same problem, cross-checking results, allowed us to gradually drop the inevitable initial "extra safety margins".

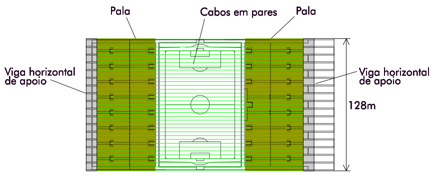
This process, which took advantage of all the available resources, had to be convergent. Its fruit was after all the construction of a building – there were deadlines and budgets to stick to. Pragmatism and flexibility were needed and we had to incorporate the limits that we could not exceed.

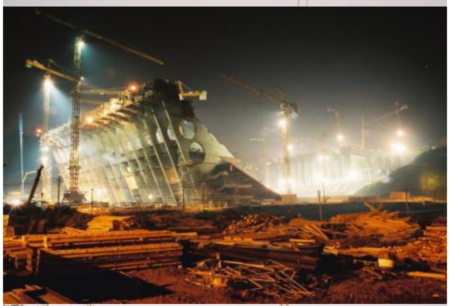
The variety and complexity of the technical problems that this project arose constituted a great challenge for our team but, simultaneously, an opportunity to learn that we did not waste.

A word for the role of the Client - the success of the Project was only possible with total commitment and trust from the Client – we had it throughout the whole process in the person of the Mayor of Braga. Contract strategies have been developed and put in place to allow for flexibility and fit a process that was far away from being closed. Time schedule and costs lived together with the technical demands and aesthetical aspirations of the Project.

It is rewarding to realise now that to talk about the stadium's structure is also to talk about its architecture, and that to explain its architecture is to tell the story of the engineering problems it brought up and how they were overcome.







General description

The Braga Municipal Stadium is located in Dume, in the Braga Sports Complex which will also include a sports pavilion and an Olympic swimming pool.

The most noticeable element of the stadium is without doubt its roof, which is made up of pairs of full locked coil cables, spaced 3.75m apart from each other, which support two concrete slabs that cover the two stands of the stadium. Its span (202m), and the fact that the cables are free in the central zone were its main challenges.

Due to the innovative nature of the project, several entities were involved. Three studies were carried out with regard to its wind behaviour (rigid and aeroelastic).

The rainwater is drained from the roof (similar to the Portuguese Pavilion in EXPO 98) along one side only, collected in two stainless steel "aqueducts", running along the plinth of the embankment. The variation in the length of the various pairs of cables along the roof ensure its required scope to the hill.

The front edge of the two concrete slabs of the roof support a triangular transversal truss, initially designed as stiffness beam, but modified to accommodate the floodlights and loud speakers.

The roof is supported on two large beams at the top of both stands – east and west, where the cables are anchored.

The east stand is structurally made up of 50m-high uprights that are "pierced" by the slabs of the different floors of foyers of the stadium. Its longitudinal stability is guaranteed by the existing slabs under the steps of the stands. The uprights of the east stand, which are only 1m thick, are extremely elegant.

After the roof, the west stand is perhaps the most complex structural element, due to the diversity of the problems it involved: the uprights anchored in the rock, the functioning of the structure with the ground, compatibility between the structural functioning of elements with very different stiffness, the laying of foundations in unstable embankments. Among the several solutions encountered it is difficult to pick out one worthy of special mention.

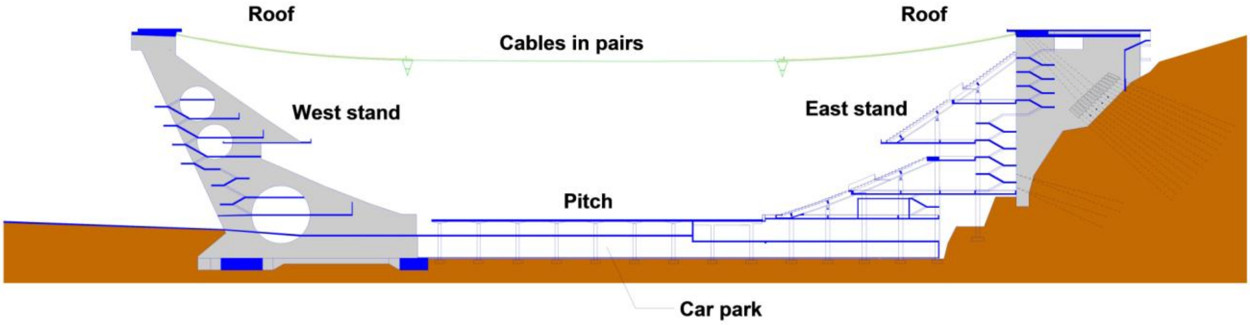
The so-called pitch is in fact the building that is hidden underneath it self. It has two floors and covers the whole area of the pitch. It includes a car park, changing rooms and all the EURO 2004 backup services. It did not cause particular structural difficulties apart from the control of the consequences of shrinkage and temperature variations, which led to the installation of bearings between the columns and the slab for the pitch platform, especially well integrated into the architecture.

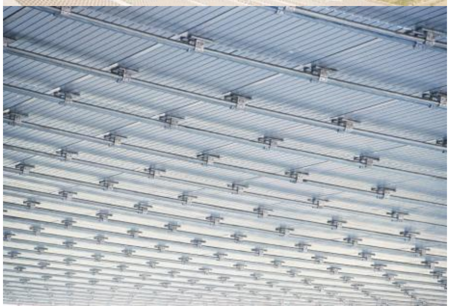
The excavation and stabilisation of embankments that preceded the construction of the stadium was in itself a huge task. In total 1,700,000 m^3 of hard rock and gravel were excavated, which led to the need to contain enormous rock embankments, in which, unfortunately, the fractures were in an unfavourable direction. The embankment was contained with a net of anchors and rock bolts to guarantee its stability.

The behaviour of the embankments is assessed through a set of in-place inclinometers and anchor load cells, linked to the stadium monitoring system.

A building of this scale naturally needs an important set of infrastructures, the most important of which were the deviation of a sewerage collector from Braga and of a watercourse that crossed the land.

This text details the most important aspects of each of the elements briefly described above.




The Roof

The concept was to build a set of suspension cables, spaced 1.875 m apart, suspended from the beams at the top of the uprights, supporting the two independent concrete slabs that covered each stand.

The geometry selected for the roof resulted from a compromise between the aim of the architect (extremely subtle inverted arch) and the value of the force produced on the structure by the horizontal component of the cable forces.

The selection of the kind of cable was also extremely important as it would influence the definition of the shape and technological characteristics of the roof. Two options were possible: full locked coil cables and sheathed cables. After studying the different characteristics of the two solutions in terms of durability, anchoring devices and dimensioning, full coil cables were selected, which led to smaller sections.

In the tender phase, given the vital role of the “specific” technology of each cable manufacturer, it was decided that for the cables system a Design/Build contract should be put in place, where the Contractor was allowed to propose changes to the original design developed by AFAssociados. Responsibility for the roof project was therefore shared by the Afassociados project team and the Contractor ASSOC-Obras Públicas, ACE/Soares da Costa together with the manufacturer of the cables – Tensoteci

As well as standardising the concrete slab height, the only modification worthy of mention from the initial project to the one that became the tender winner, consisted in the grouping of the cables in pairs, with spacing between each pair 3.75 m, two times the initially planned 1.875 m.

The suspended roofs gave rise to special challenges for the structural engineers, caused mainly by the action of the wind and the construction process.

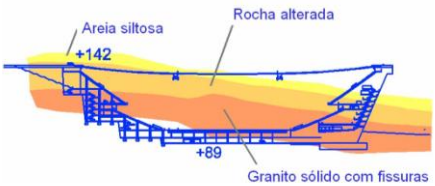
Due to its unique scale and features, a roof of this kind cannot be calculated using code values, standard recommendations or prior experience.

To study the behaviour of this roof all the customary project procedures have to be rethought starting with the essentials, from establishing the values of the actions to be considered to the forecasting of the response of the structure and the possible interaction between the two. It was therefore necessary to use physical models (tests in small-scale models) to complement the usual mathematical models (algorithms calculated using computerised simulations) which, in this case, no matter how sophisticated, were not sufficient on their own to estimate the value of the actions, namely regarding the wind action. Hence, a combination of physical models and mathematical models were built to simulate the behaviour of the structure.

Therefore a high number of calculations and independent model tests had to be carried out, both with regard to the initial solution and the final solution of the roof, which are both described further below.

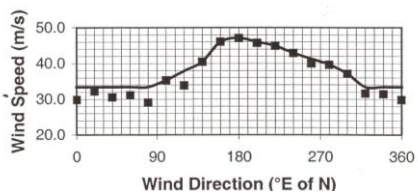
The construction process also brought up big challenges, such as how to efficiently build the roof covers many metres above a solid base, in an enormous area. And what would be the effect of the construction process on the final geometry of the cables and, consequently, on the roof covers?

This solution for the roof naturally requires a structure that resists the enormous horizontal forces generated by the cables, at a great height above the foundations. As such, it was crucial to carefully dimension the uprights of the east and west stands. The west stand benefits from the presence of sound granite at the level of the roof cables, to where the forces of the cables are transmitted.



Wind analysis and wind effect

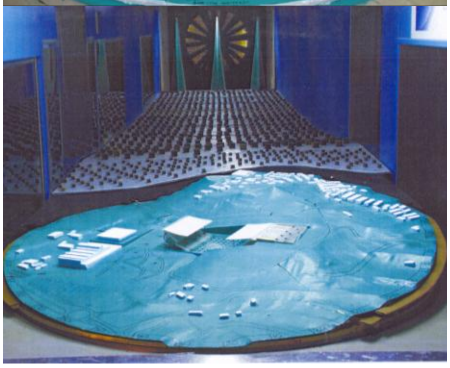
A modern and automatic meteorological station had been set up in the neighbourhood of the stadium, in Merelim, although at the date of the project it had only been functioning for thirty months. This anemometer provides average and maximum wind speeds and directions every ten minutes. The data is subsequently processed according with established statistical methods, which allow curves to be produced showing the speeds to be taken into account at the stadium location, for the various wind directions.



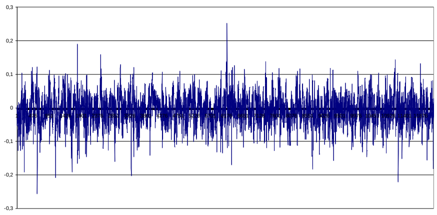
To obtain the "description" of the design wind at the construction site for 100-year return period the data provided by the Merelim Meteorological Station were statistically processed and suitably "corrected" taking into account the "meagre" thirty months of records.

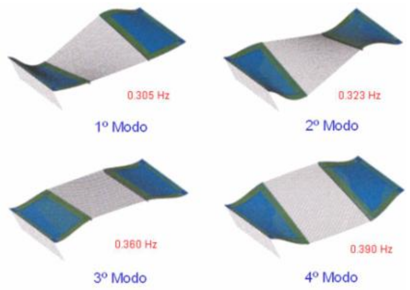
The extreme analysis of the anemometer data used the Leiblein method on independent gust velocities. The analysis for mode and dispersion was done on the square of the velocities as this provides a better fit to the Fisher Tippet type 1 distribution of extremes.

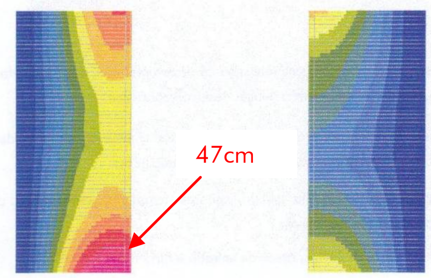
To determine the effects of the surrounding topography on the average speed and on the intensity of turbulence arising from the airflow in the vicinity of the stadium, tests were undertaken in a wind tunnel on a rigid model in scale 1:1500. This model was made by Rowan Williams Davies & Irwin Inc. (RWDI, Canadá).

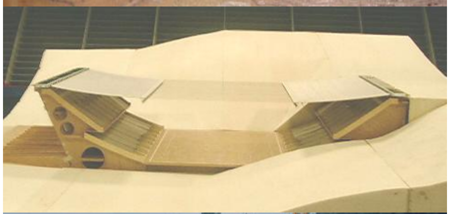


The time history of dynamic pressures at several points of the roof, caused by the design wind for each of the directions considered, were obtained using wind tunnel tests on a rigid model at scale 1:400. The roof of the model was instrumented with pressure sensors in 200 points distributed over its upper and lower surface. The measurements were registered automatically, obtaining the respective time series for wind in 36 different directions spaced 10 degrees apart. This physical modelling was made by Rowan Williams Davies & Irwin Inc. (RWDI, Canadá).









The calculation of the response of the structure to the dynamic action of the wind described by the history of pressures previously obtained was done in two different ways.

The first was a determinist dynamic time history analysis over time, through direct integration step by step of the dynamic equilibrium equations of the structure based on a linear elastic analysis of a shell finite element model with a geometric stiffness matrix that was assumed as constant. The geometric stiffness matrix was obtained using the axial forces of the cables due to the permanent loads. Through this analysis the dynamic response of the structure to the dynamic action of the wind could be calculated. The maximum displacement calculated was 47centimetres.

The second method was a probabilistic dynamic analysis using the Orthogonal Decomposition Method. This method is based on the principle that an unsteady multivariate pressure field can be usefully simplified by projecting it in a space generated by the eigenvectors of the covariance matrix of the original field. This method has two big advantages. First, the new fields (pressure modes) are mutually uncorrelated. Second, the energy content of the complete multivariate field is usually well represented by few components in the transformed space, allowing the representation of the effective pressure field by mean of few pressure modes. This analysis enabled to estimate the quasi-stationary component and the resonant component of the response of the structure in terms of stresses and deformations. These values were used to scale the different structural elements of the roof.

The mathematical modelling based on the results of the tests in the wind tunnel with the first physical models did not guarantee the non-occurrence of aeroelastic behaviour of the roof. Indeed, this kind of behaviour of structures requires highly complex specialised studies. The most delicate problem consists of the possibility of wind flow around the structure causing resonant behaviour of the construction. These movements can be forced – vortex shedding – or interactive – divergence, gallop or flutter. All these kinds of behaviours have specific technical definitions.

Although it was decided that a behaviour of this kind would be extremely unlikely, a decision was made to develop aeroelastic physical models to be tested in a wind tunnel.

The aerodynamic stability of the initial solution was demonstrated through tests on a aeroelastic model at scale 1:200, made by Danish Maritime Institute (DMI, Denmark).

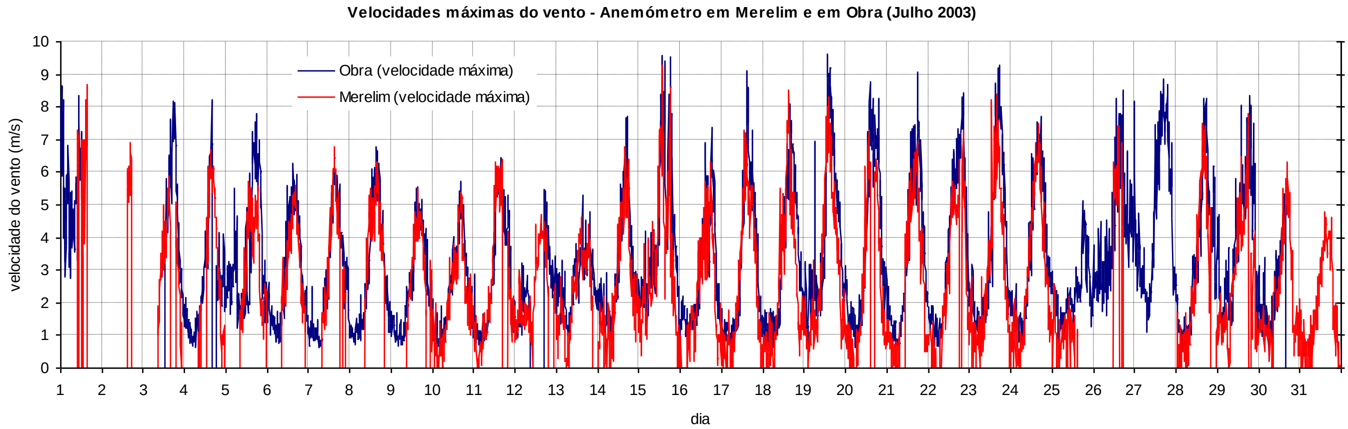
The absence of aeroelastic instability in the final solution was proven through tests on a aeroelastic model at scale 1:70, made by Politecnico di Milano.

Both models demonstrated the aeroelastic stability of the roof, with the measured maximum deflection almost equal to the movement calculated.

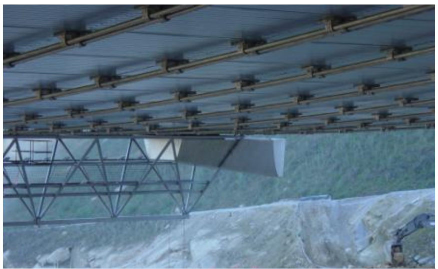
However, in the central zone, where the cables are free, it is possible that they may show some dynamic behaviour. Therefore, a decision was made to connect pairs of cables to each other and to add dampers to them.

In order to confirm the estimated values of the "design wind" based on the measurements of the Merelim anemometer and to dissipate any doubts concerning the intensity of turbulence of the wind at the stadium site, a local anemometer was installed at the construction site. The measurements recorded have been compared with the data from the Merelim meteorological station.

The following graph shows the maximum velocities recorded in 10-minute periods in the past month of July. The coherence between the readings is pointed out.



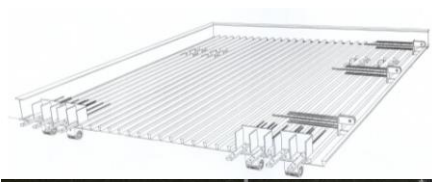
To study how sensitive the bending moments of the roof slab are to variations of the forces in the cables, a probabilistic analysis was undertaken. The roof is considered to have been made of a reinforced concrete slab supported on n cables and the bending moments were considered in m points of the slab. For a particular load combination, the n cables have computed strains given by the vector ε. Several factors can produce a random variation Δε of these strains (differences with design pre-stress, non-uniform distribution of temperature, differential creep). It is considered that these effects are represented by the vector of random variables Δε with mean value μ and standard deviation σ. The problem is then to estimate the probability Pf, that the generated random bending moments M will be larger then the slab ultimate resistance moments Mu at any of the m points of the structural plate system. To solve this problem a stochastic simulation is used based on the Monte Carlo method combined with the "Object Oriented Method" simulation to generate the random variables Δε.



Drainage of rainwater

The rainwater is drained off the roof in the east embankment direction, with one percent fall, which is achieved by varying the length of the pairs of cables that support the roof. Two large spouts in duplex stainless steel, suspended from the concrete slabs channel the water to the "aqueducts", which are also made of stainless steel, which lead to the rainwater network and the watercourse existing at the stadium site. The aqueducts, approximately 40 m long, of which 27 m is overhanging, are supported on the ledges of the embankment on columns with different lengths, as the ledges are sharply sloped. The lateral stability of these aqueducts is guaranteed by a pair of buttresses anchored to the rock of the embankment.

The dimensions of these two devices were established through a study of the water flow, taking into account the height of the fall, limited by the foreseeable movement of the roof due to the wind.



The construction process

First of all, the Architect wanted to see the roof as a continuous surface standing over the cables.

For predictability reasons of the roof behaviour, the slab is connected to the cables only in the normal direction allowing relative tangential movements between them. This option has many advantages concerned with the response to thermal actions, to the shrinkage of the concrete roof slab and to the dynamic load of the wind.

To drain the water, the roof should have a 1% slope from one side to the other. The size of all the cables should then be different.

The question of how to build a 14.400m2 slab, 50m from the ground, over an elastic

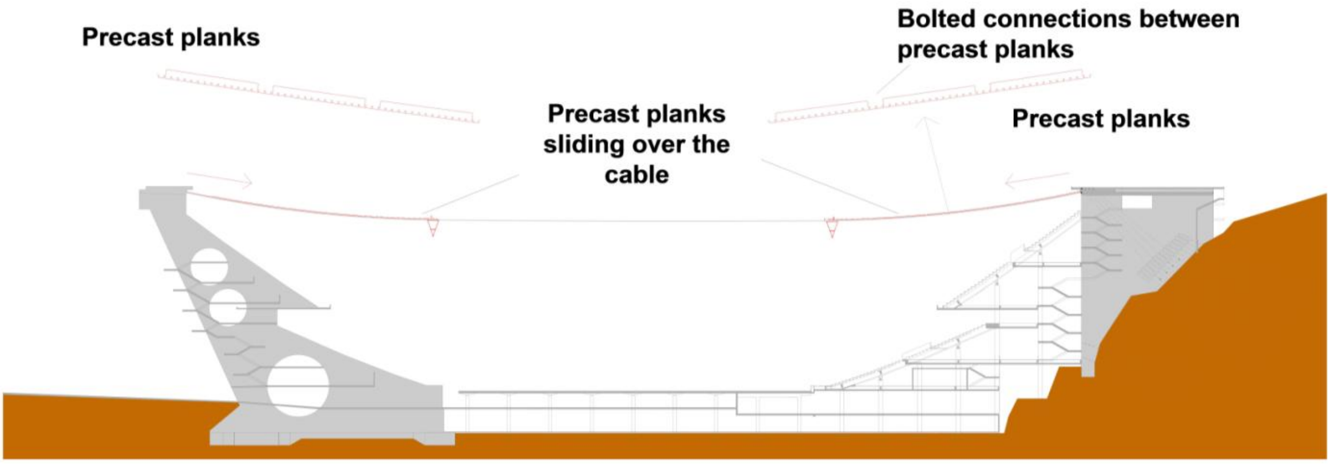
support was a big wormy. What effect would the construction sequence have in the final geometry of the roof?

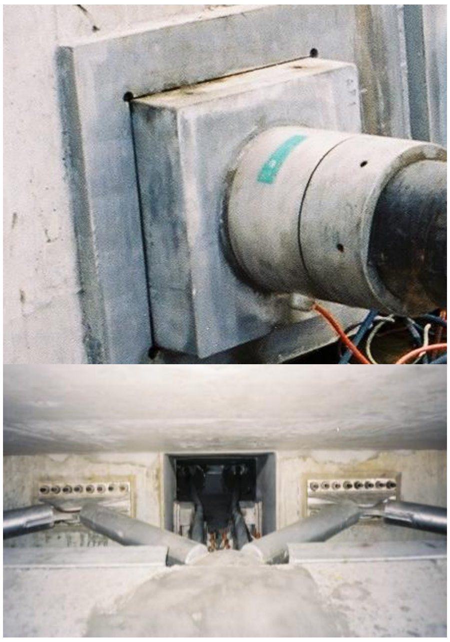
The Portuguese Pavilion in Expo 98 had been built propped from the ground, which was unthinkable for such a big roof hanging 50m from the ground. The construction sequence of stress-ribbon bridges and the Dulles airport building in Washington gave us the direction – precast planks sliding over the cables with a minimum layer of concrete pouring to minimize the problems that different deflections would generate.

The roof construction process entailed three fundamental problems: the detailing of the covers, the assembly system and the effect of the assembly process on the final shape of the suspended cables.

The reinforced concrete slab is 240millimetres thick, having arrived at this value by balancing the need for a stabilising mass while minimising its weight. For practical and economic reasons the installation of props and formwork had to be avoided. Hence the option for prefabricated elements was inevitable. The panels selected measured 1.8 metres by 3.75 metres. The lower face of the panels are lined in steel sheeting, which overlaps the edge of the prefabricated concrete to provide the formwork so as to enable the panels to be joined in situ. The panels also have metal parts that enable them to be interlinked with bolts during the assembly process.

The prefabricated elements were assembled over the cables, on top of the stands. Each new piece is linked to the previous piece with bolts and the pieces were slid along the cables using gravity. When all the elements were in position the transversal and longitudinal joints between the panels were concreted.





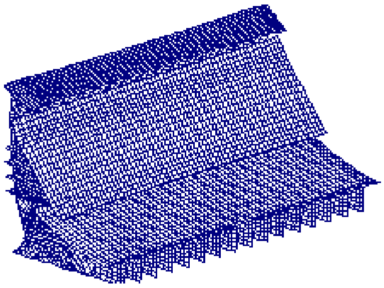
Control of geometry and monitoring

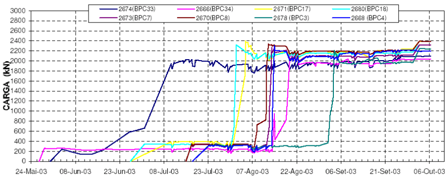
The installation of the cables and the precast panels of the roof was an "authentic load test" of the structural elements of the stadium. Therefore the response of the whole structural system, in terms of stresses and deformations, was carefully monitored so as to identify and analyse any "deviations" from the predicted behaviour in advance.

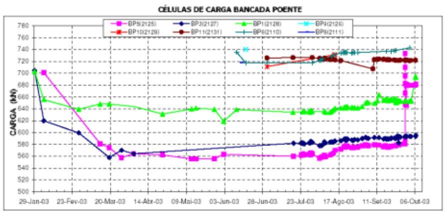
The "phase by phase" response monitoring of the structure during assembly of the roof as well as its "mechanical interpretation" guaranteed that there would be no "surprises" in the final geometry intended for the system of cables that give this roof its unique form.

The final form of the roof would always be dependent of the weight of the cover, the force installed in the cables and the stiffness of the support elements (top beam and uprights of the stands). The relative importance of all of these factors was assessed, and in monitoring the response of the structure all the components of each factor had to be included.

In order to do so it was necessary to tightly control all the loads applied to the cables of the roof. Together with the register of charges applied, the geometry control







operations, using the topographical surveys and the collection and treatment of the information furnished by the monitoring system ("internal" instrumentation of the structure and instrumentation of the rock massifs and foundations), were essential to analyse the behaviour of the structure during assembly of the stadium roof.

The behaviour of the structural elements of the stadium during assembly of the roof was monitored using the information collected by the instrumentation system installed, namely:

- Load cells in the roof cables.
- "Internal" instrumentation of the concrete structure (strain gauges, tiltmeters and thermometers in the uprights of the East Stand).
- Instrumentation of the rock massifs and foundations.
- Load cells in the anchors to the earth.
- In-place inclinometers.

The organisation and interpretation of the data collected during the whole process allowed, until the end of assembly of the roof elements, the mathematical models used in the design phase to be constantly checked and possibly corrected so as to be coherent with the values measured on site. This led to the definition of the criteria to establish and correct the theoretical reference geometry of the roof so as to take into account the actual behaviour of the structure and the climatic conditions on the date in which the final adjustment was made to the geometry planned from the start.

It is pointed out that any deviations in the geometry of the roof and/or in the forces installed in the cables in relation to the planned values would lead to the need for a careful analysis of the impact on the final form of the roof and the final forces of the cables (taking into account the code limits used in the design phase).

When the new Braga Municipal Stadium is in use its structure will be monitored by a system electronically controlling the different structural parameters, both static and dynamic. This will be a computerised system, allowing either discrete or almost continuous data to be registered, depending on the nature of the measure and the location of the instrument.

In addition to the static instrumentation sensors already mentioned (both in the concrete structure and in the rock massifs) dynamic monitoring will also take place, made up of 6 triaxial accelerometers placed on the points of highest amplitude of vibration of the roof and by cells measuring the wind pressure at various points on the underside and top of the roof covers.

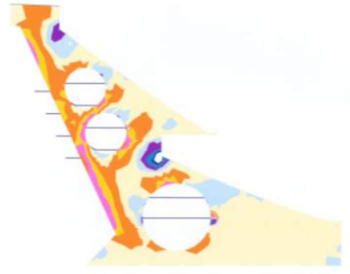
The East Stand

At the end of the road giving access to the stadium, the East Stand rises from the ground at a level of +98.00. The stand is supported on sixteen vertical blades (uprights), all of which are 1 metre thick, which begin at level +87.80 and reach level +142.85. The stands are accessed via rising and descending ramps. The descending ramps allow one to cross a wide space immediately below the level of the pitch, giving access to the West Stand. The rising ramps give access to the seats in the upper and lower stands, and all the facilities located in this stand such as walking zones, WCs, hospitality boxes and bars.

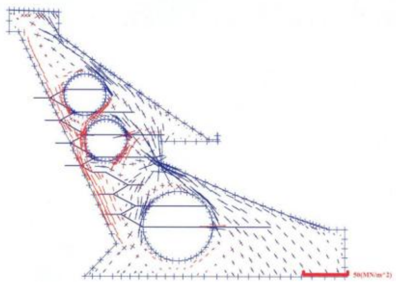
Visitors ascend the stand through stairs located between the uprights, which from level +110 onwards, have plinths placed at the intermediate levels (protruding from the uprights). There are also two panoramic lifts to transport loads and people between level +98 and level +112. The hydraulic and electrical infrastructures are placed inside the uprights and the slabs, from the level of the foundation to the level of the roof.

Structurally the East Stand functions without any dilation joint. Therefore the set of the 16 uprights with the slabs of the floors and the stands stabilise the structure of this stand in relation to both vertical and horizontal actions.

From the start of the design phase it was understood that a “suspended” roof between the two stands would have its main stumbling block on the structure of the East side, where the cables are anchored more than 50 metres above the foundation level. The structure of this stand should therefore adjust to the geometry of the uprights in order that the result of the combination of the gravitational actions of the stand and the high forces transmitted by the roof minimise the imbalance of moments at the level of the foundation. In a first phase this goal was partially achieved. With the evolution of the project and the incorporation of the functional demands of the stadium, equilibrium at the level of the foundation was not fully achieved, leading to a considerable adjustment of the solution at the end.



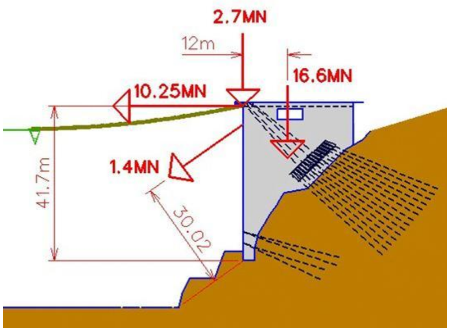
Several calculation programs of two-dimensional and three-dimensional structures were used in the analysis of the structure of the East Stand, representing the whole structure of the stand. Regarding the actions, the seismicity conditioned the dimensioning of the vertical elements, owing to the substantial “weight” of the highest level, i.e. at the level of the roof. Given that it is a structure without dilation joints, the temperature and shrinkage also proved to be actions of great importance in the final design. It was due to these actions that the floor at level +93.24 was designed completely disconnected from the uprights, creating a system of independent frames which, however, were supported on the foundation of the uprights.

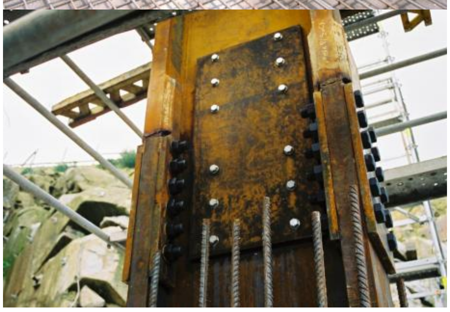


The uprights are made from reinforced concrete (C35/45 + A500). The architecture of the lateral concrete faces designs all the stereotomy of the formwork. Visitors can circulate horizontally through three large circular openings, one 14 metres in diameter and the other two 8.5 metres, which are crossed by slabs approximately 125 metres in length.

The floor slabs are supported on the uprights and on metal beams whenever the support position is the circular openings. In this zone the steel beams act together with the slabs as composite steel and concrete girders. The stairs are in reinforced concrete and are supported between the uprights, spanning an open bay of 6.5 metres. On top of the uprights is an extremely stiff beam following the direction of the roof cables (top beam), which guarantees the transition between the roof cables and the uprights.

Regarding the foundations, there are three types of geological-geotechnical strata (ZG1, ZG2 and ZG3). This heterogeneity was especially important, and several analyses were carried out representing the global behaviour of the structure with ground-structure interaction. Taking into account the sensitiveness of the structure to the subsistence shown in the numerical models, the taken option was to replace the earth of lesser quality with concrete, thus guaranteeing the whole structure is based on rock.





The West Stand

The West Stand of the stadium is "carved" in a granite massif whose upper level is at the level of the square that gives access to it.

This is the stand that will accommodate all the journalists and VIPs during Euro 2004, and also contains areas set aside for restaurants. The areas occupied by the floors below ground level (+98.00) are for circulation and also house the changing rooms, a medical post, ambulance services, etc. Visitors can move vertically via stairs and lifts, most of which are panoramic.

The relation between circulation zones located under the stands with the "striking" rock embankment, characterised by irregular cuts and pronounced fractures, had to be emphasised in the Project. Therefore the circulation zones and vertical communication were as understated as possible, thus giving pride of place to the rock and its connection to the uprights of the roof.

Taking advantage of the fact that the upper square (West) is at the same level as the roof, the horizontal actions transmitted by the roof cables were stabilised by anchoring directly to the massif. Eighteen uprights were positioned in this transition zone, between the roof and the rock, all 1 metre thick, which are adjusted to the irregularities of the embankment.

The slabs of the floors are inverted, that is, their lower face is aligned with the lower face of the beams that support them. Composite concrete and steel slabs are laid over these lower platforms, which are supported on concrete blocks and span bays approximately 2.4 metres wide. This allows a gap of approximately 65 cm in height between the lower slab and the composite slab which used for the passage of pipes containing the hydraulics, electrics, heating and ventilation installations. The steps of the stands are prefabricated and are supported on pre-stressed and reinforced concrete angled beams, continuous along the 16 alignments in the direction of the axes of the uprights. Prefabricated panels were placed immediately below the steps of the stands. Given the characteristics of the massif of the foundation, the foundations of the structure are of the direct kind (footings). To support the columns and uprights in zones of fragmented massif and around the crest of the embankments local stabilisation was undertaken using definitive anchorages.

The frame structure of the West Stand could have been considered self-sufficient in terms of bracing the horizontal plane, as is the case for most structures of this kind. This possibility was limited given the slenderness of the columns and the almost always eccentric manner in which the beams are supported. Therefore the slabs at level 112 and 116, floors 2 and 3 respectively, were taken advantage of, functioning as rigid horizontal diaphragms, conferring appropriate bracing of the horizontal actions despite the low number of connections from the slabs to the uprights. The irregularity of the level of the floors and the slopes of the stands led to the need to undertake the whole calculation on global three-dimensional models. These models represent the beams, slabs, columns and walls, in accordance with the spaces required for the architecture.

This highly hyperstatic structure is very sensitive to settlements of supports, which led to the meticulous control of possible settlements not only through calculation of the structure considering the ground/structure interaction, but also by the improvement and standardisation of the behaviour of the foundation ground.

The reactions of the roof and the horizontal components of the reaction of the stands determined the dimensioning of the uprights. As this was an essential component of the global stability of the stadium, and as the uprights were founded in zones of differing geotechnical characteristics, models had to be developed representing the ground/structure interaction that allowed the design of the anchors to be confirmed, and the state of permanent compression between the uprights and the rock embankment to be verified. As such, it was possible to confirm the global equilibrium of the uprights in relation to the loads transmitted to them and proceed with their

internal dimensioning, including the foundations.

The upper level of the anchors transmits “almost directly” the majority of the horizontal load to the rock massif. The lower level of the anchors play a crucial role in correcting the direction of the reaction of the upright in its foundation, the result of which is channelled to the interior of the massif, which is necessary given the fracturing of the massif under the foundation.

Given the sensitivity of the structure to settlements, and taking into account the essential role that the anchors played in the global equilibrium of the structure of the stadium, the construction phases had to be defined so as to allow the structure to become functional on schedule. The fact that there were several pre-stressed parts and that 5 uprights were founded in hard core added to this necessity. This need, on the other hand, went against the factor that the force of the anchors should not be applied in their entirety before the roof was finished, as this would lead to an exaggerated compression in the massif. Several possible phasing scenarios were therefore simulated and calculated, before deciding on the application of just 20% of the force of the anchors before constructing the roof, leaving the final stressing for afterwards, which led to the need to check the resistance capacity of the different parts taking into account the forces resulting from the application of the loads in a hyperstatic structure already built.

The construction of uprights 1 to 5, laid on hard core (therefore more liable to deformation) began with the construction of a foundation beam anchored to the massif, with the whole of the planned force immediately applied so that the final structure could be built after the subsistence had occurred. The uprights laid on rock (6 to 18) were furnished with provisional anchors that endowed them a state of pre-compression, so as to minimise the effects of the subsistence expected due to the high level of fracturing of the massif. These anchors were deactivated at the same time as the stressing of the definitive anchors.

The "Pitch"

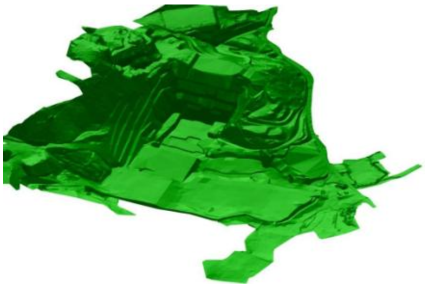
Vehicles enter the stadium through a prefabricated tunnel with an arched ceiling, inserted into one of the embankments that border the stadium, to the west of the pitch. The tunnel leads directly to floor -2 (+87.80). This floor includes a large car park for passenger vehicles and coaches. Next to the East Stand is the area of the “programme” defined by UEFA for use during EURO2004, encompassing an auditorium, reception halls, working rooms, etc. This floor also houses the water tanks for fire-fighting purposes, and other electrical installations of the stadium. Floor -1, at level +93.24, consists of a large space for circulating between the East and West Stands, and also an area for the changing rooms, coaches and referees. This area is delimited by a concrete wall. The pitch is located at level +98.0 and measures approximately 125x80 m2. All around the perimeter of the pitch is a trench protected by metal railing, which allows light to infiltrate into floor -1 and at the same time enables people and vehicles to circulate in the event of emergency. The drainage of the “relvado” includes drains installed both on the pitch and suspended under the surface. The drained water is channelled to a peripheral tunnel running along the

perimeter of the pitch.

Like in the East and West Stands, the electrical and hydraulic infrastructures, such as lighting, fire detection systems, CCTV, etc in areas where the concrete is in view are embedded inside these elements (slabs and columns).

Structurally the zone underneath the pitch is formed by circular columns capped by circular sections of diameter 0.7 metres, which support the mushroom shaped slabs of floor -1 and the ground floor. These columns are spaced 9.35 m apart in one direction and 7.5 m in the other. The slab of floor -1 is solid concrete and has a constant thickness of 0.35 m. The slab supporting the pitch is 0.5 m thick and supports, as well as the loads expected on the pitch, the whole system comprising the field of play, including the impermeable and drainage systems, making a total average thickness of 1.10 metres. The columns are capped by conical column heads with a minimum diameter of 0.70 m and maximum diameter of 3.90 m. There are columns with the foundation located immediately below floor -1 and others under the ground slab of floor -2. The different stiffness between these two types of columns led to the placement of neoprene bearings on top of the most stiff columns (founded below floor -1), thus preventing strong forces resulting from the shrinkage of the concrete and thermal variations. The need to place these bearings affected the finish between the top of the columns and the conical column heads, creating an identical appearance among the columns containing the bearings and those that do not.

The foundations are direct footings.



General excavation and slope stabilisation

To build the stadium inside a "Stone Mountain" it was necessary to extract approximately 1.7 million m³ of rock and gravel. Despite the fact that the initial geological/geotechnical survey revealed heterogeneous granite, with good mechanical characteristics in some zones and others with large alterations, during the course of the excavation the worst case scenario was confirmed. The larger embankment (East) was extremely fractured, sloping in the direction of the embankment itself between 45 and 50°. This meant it was impossible to obtain a vertical wall as had initially been intended, leading to the creation of ledges and contention of the whole embankment. The excavation therefore had to be much slower, as the designed contention (anchoring and bolting) had to take place, from top to bottom, at the rhythm of the excavation. Despite this, there were areas in which it was impossible to avoid slipping of blocks, which resulted in the visible surfaces of the rock embankment – the "flats". As a result of this slipping, and a fault meanwhile detected in the NW-SE direction, the stadium had to be shifted 20 m west of the initially planned location. The embankments were stabilised with definitive anchoring and bolting, using high-resistance steel rods of diameters 36 and 32 mm respectively. The force installed in the anchoring is 600kN and 835/1030 steel was used.

The west embankment, much smaller than the east one, was far easier to stabilise as the slope of the family of fractures was favourable. This embankment was also stabilised through anchoring and bolting.

The embankments were monitored with 10 load cells in the anchoring and four in-place inclinometers, each of a total length of 20 metres. The readings of these sensors are regularly monitored, so as to assess any unexpected phenomena in the massif. In the future both the load cells and the in-place inclinometers will be integrated into the global monitoring system of the structure of the stadium that will automatically and permanently manage all the sensors installed.



Infrastructures

The land where the complex will be located was crossed by a watercourse that ran along the valley and by a sewerage collector from the city of Braga. Both had to be deviated, first temporarily during the construction phase, and definitively at the end. The watercourse was channelled under the current East Square, discharging into an open canal. The different level between the east square and its connection downstream was overcome through several waterfalls. The sewerage collector now runs along the inside of the technical tunnel that links to the stadium roundabout, under the access avenue. This tunnel, made with prefabricated box culverts also transports the electricity and telephone cables and the public water supply branch.

The implantation of each of these infrastructures led to the digging of deep trenches (15 m in some cases) and the adoption of several solutions for its foundation, given the heterogeneity of the land crossed, which varied from rock (in the stadium zone) to large layers of alluvial substances in the trench zone.

Global Quantities

Excavation works	**August 2000 to February 2002**
• Rock excavation volume	1.013.515 m^3
• Gravel excavation volume	698.496 m^3
Slope stabilisation Works	**August 2000 to February 2002**
• Anchors	5.504 m
• Rock bolts	724 m
Structures Works	**February 2002 to September 2003**
• Concrete	88.958 m^3
• Reinforcement Steel (A500)	14.722.495 kg
• Steel Grades	1.006.815 kg
• Stainless Steel	107.296 kg
• Formwork	230.580 m^2
• Roof Full Locked Coil Cables	1.3.736 m (517.657 kg)
Landscaping	**June 2003 to September 2003**
• Pavement areas	37.530 m^2
• Green areas	9.800 m^2

The team

An engineering project is almost always a collective act whose end result depends on the contribution of the whole team. The Braga Municipal Stadium project is a good example of this:

Client: **CÂMARA MUNICIPAL DE BRAGA**

Design: **Architects:** **SOUTO MOURA ARQUITECTOS Lda**

Eduardo Souto de Moura
Carlo Nozza
Ricardo Meri, Enrique Penichet, Atsushi Hoshima, Diego Setien, Carmo Correia, Luísa Rosas, Jorge Domingues, Ricardo Rosa Santos, José Carlos Mariano, João Lima

Landscaping: Daniel Monteiro

Consultants: Arup Associates – Dipesh Pattel (Stadium Programme)

Engineers: **AFASSOCIADOS – Projectos de Engenharia, SA**

Coordination: Rui Furtado

Structures: Rui Furtado
Carlos Quinaz
Renato Bastos, Pedro Moás, Rui Oliveira,
Rodrigo Andrade e Castro, Pedro Pacheco, Miguel Paula Rocha, António André, João Dores, Sérgio Vale, Nuno Neves, Rafael Gonçalves, Andreia Delfim, Miguel Braga, João Coutinho, António Monteiro

Public Health: Maria Elisa Parente, Joana Neves

Electrical Installations: António José Rodrigues Gomes, António Ferreira, Luís Fernandes (RGA)

Mechanical Installations: José Silva Teixeira, Tiago Fernandes (RGA)

Safety: Christian Aoustin (GERISCO)

Excavation: Estevão Santana, João Burmester

Roads and Infrastructures: Estevão Santana, João Burmester

Consultants: António Silva Cardoso (Geotechnics)
CÊGÊ (Geotechnics)
OVE ARUP & PARTNERS – Andrew Allsop / Andrew Minson (Wind study)
RWDI – Mark Hunter / Michael Soligo (rigid model wind tests)
DMI – Danish Maritime Institute – Aage Damsgaard (aeroelastic model wind tests)
FEUP Construction Institute – Elsa Caetano (Dynamics)

Cables final design:

TENSOTECI - Massimo Marini
Massimo Majowietcki

SOARES DA COSTA, SA - Luís Afonso
Diogo Santos

Site Inspection: **BRAGA MUNICIPAL COUNCIL – DOMSU**

Manuel Afonso Basto
Carlos Amaral
Luís Almeida, Filipe Vaz, Eduardo Leite, Paula Pereira, Cidália Rodrigues, Márcia Rodrigues, J. Rodrigues

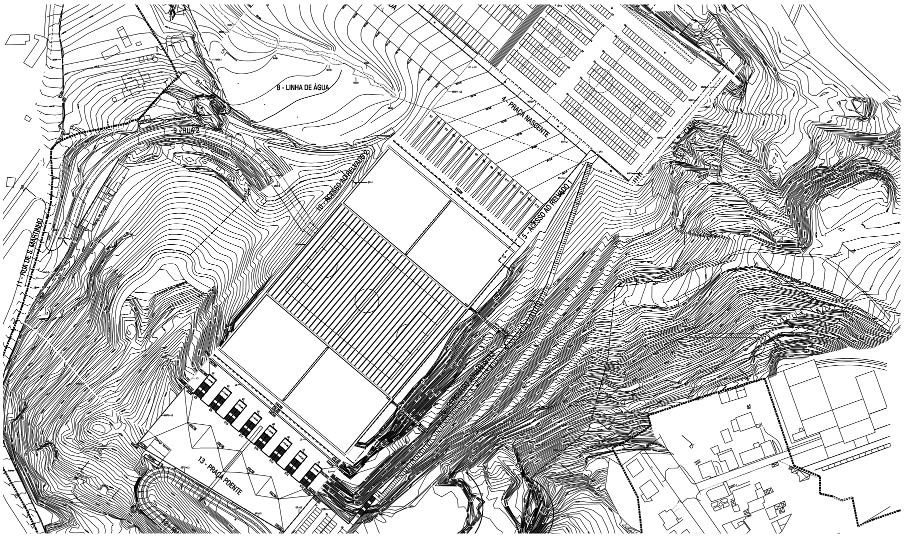
Construction: General excavation: **Aurélio Martins Sobreiro**
Adérito Faneca

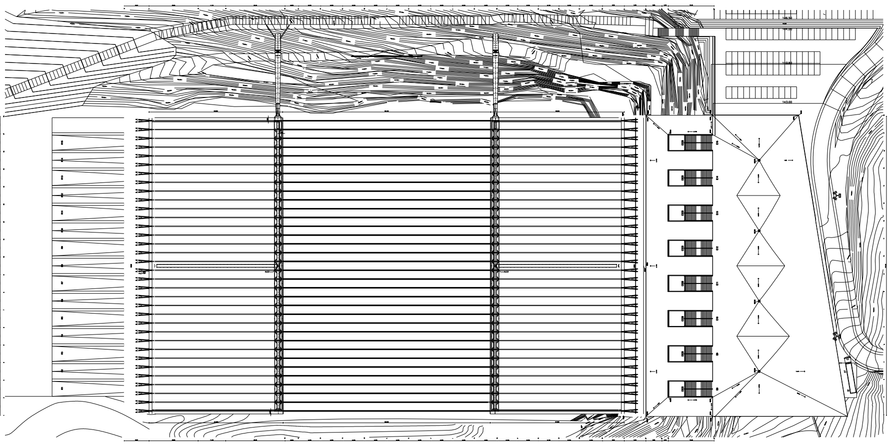
Slope stabilisation: **ACE-ASSOC / TECNASOL**
Mário Duarte, João Falcão

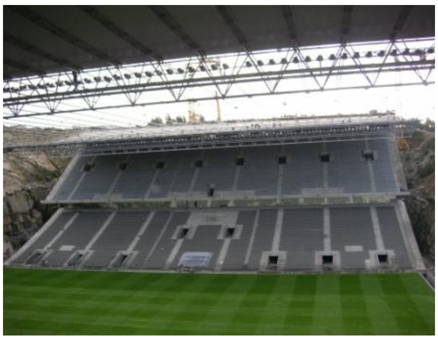
Structures, Installations Finishes and External Works. **ACE - ASSOC / SOARES DA COSTA, SA**
Lionel Correia
Jorge Oliveira, Mário Duarte,
Mário Pereira, Santos Costa

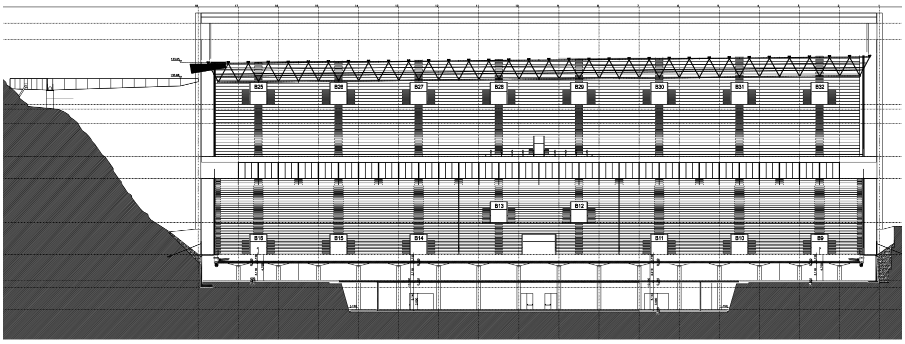
Annex

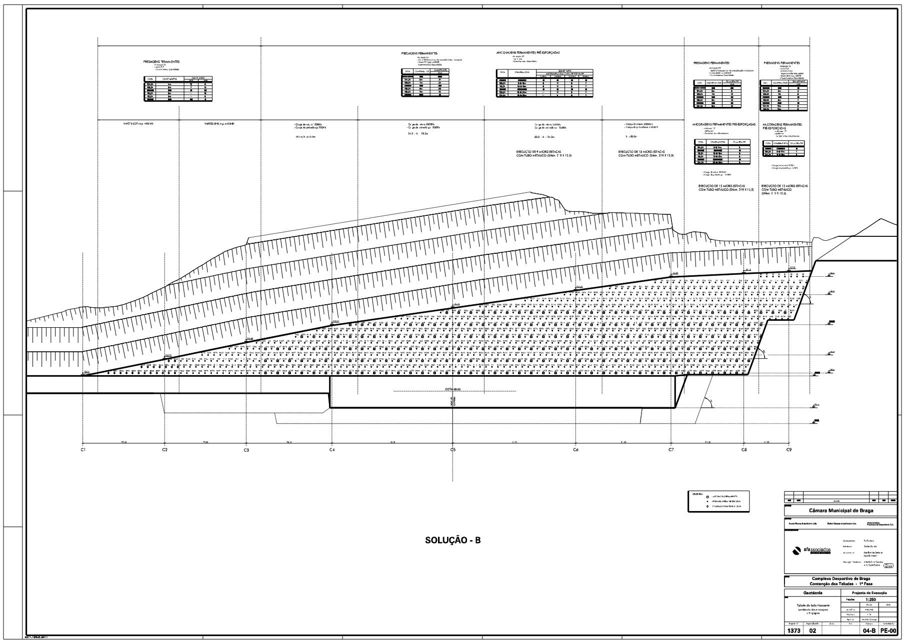
Drawing Studio







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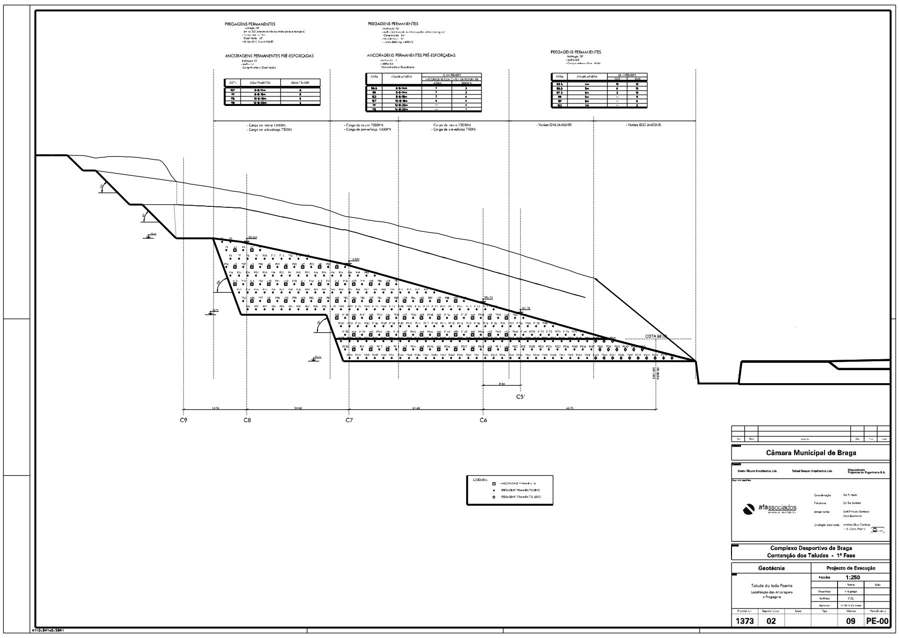
PE-00


C9
C8
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C5'
Câmara Municipal de Braga
Complexo Desportivo de Braga
Contenção dos Taludes - 1ª Fase
Geotecnia
Projecto de Execução
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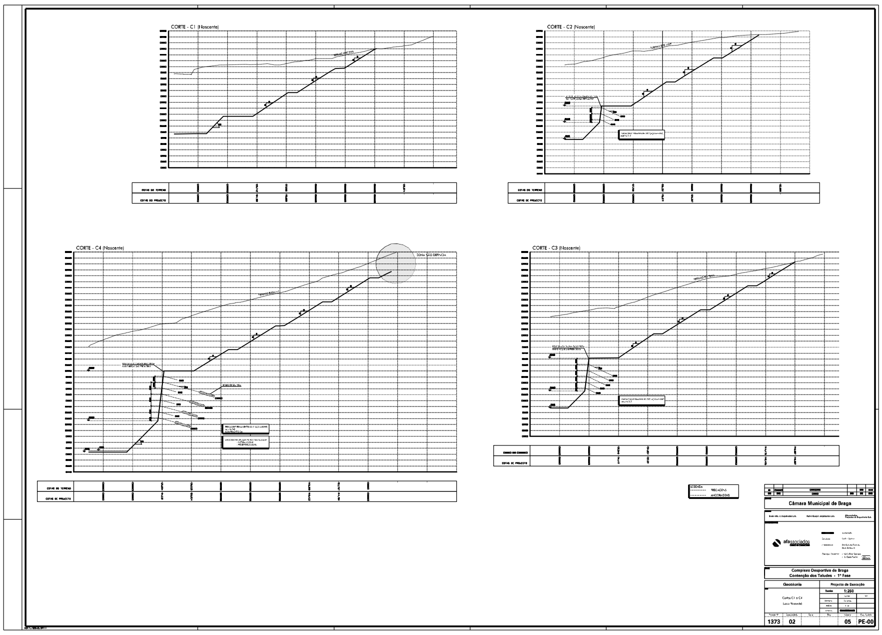
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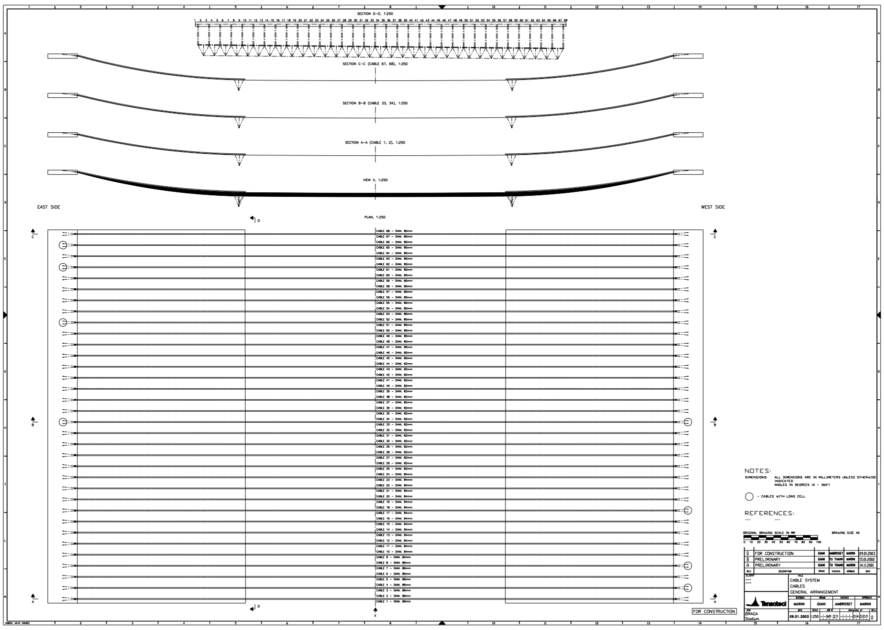
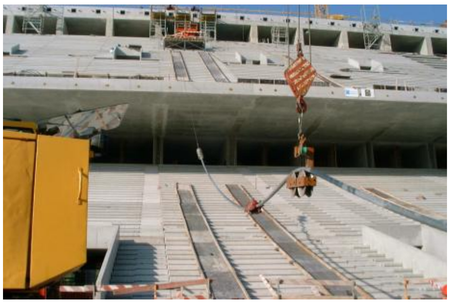
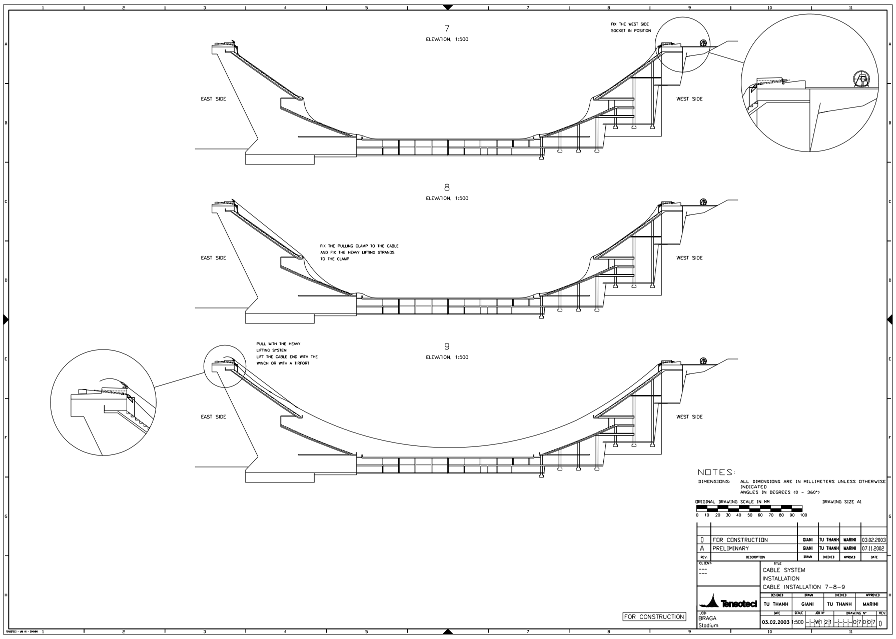
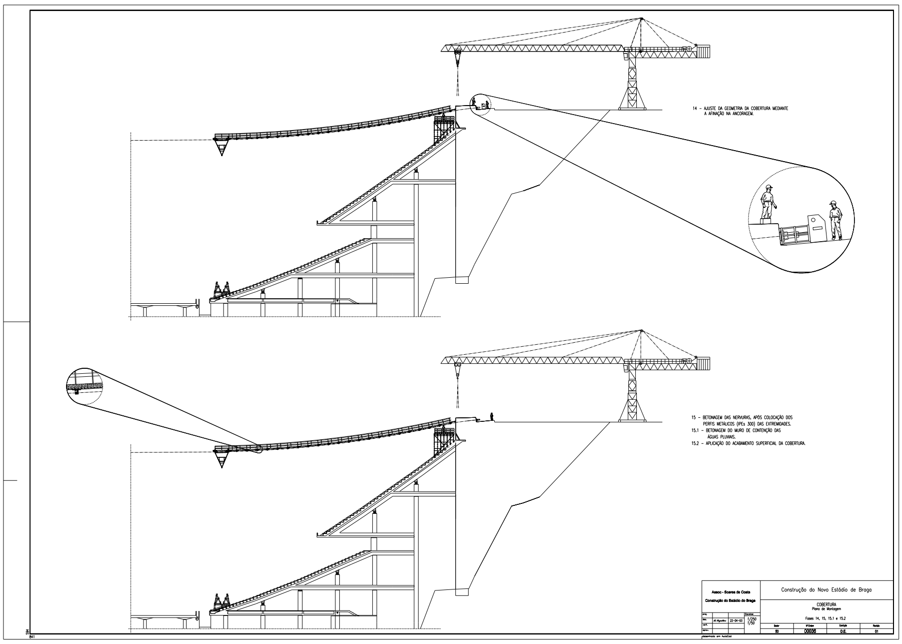

EAST SIDE
WEST SIDE
NOTES:
REFERENCES:
FOR CONSTRUCTION




7
ELEVATION, 1:500
8
ELEVATION, 1:500
9
ELEVATION, 1:500
EAST SIDE
WEST SIDE
NOTES:
FOR CONSTRUCTION
PRELIMINARY
CABLE SYSTEM
INSTALLATION
CABLE INSTALLATION 7-8-9
BRAGA
Stadium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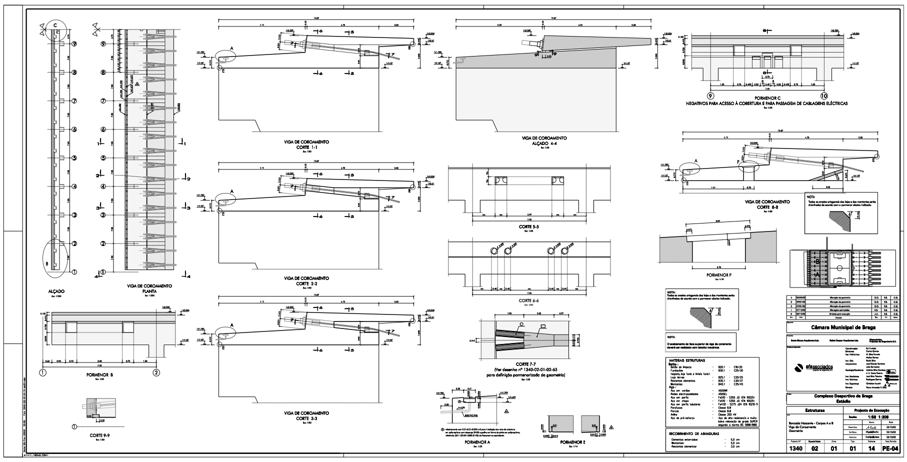
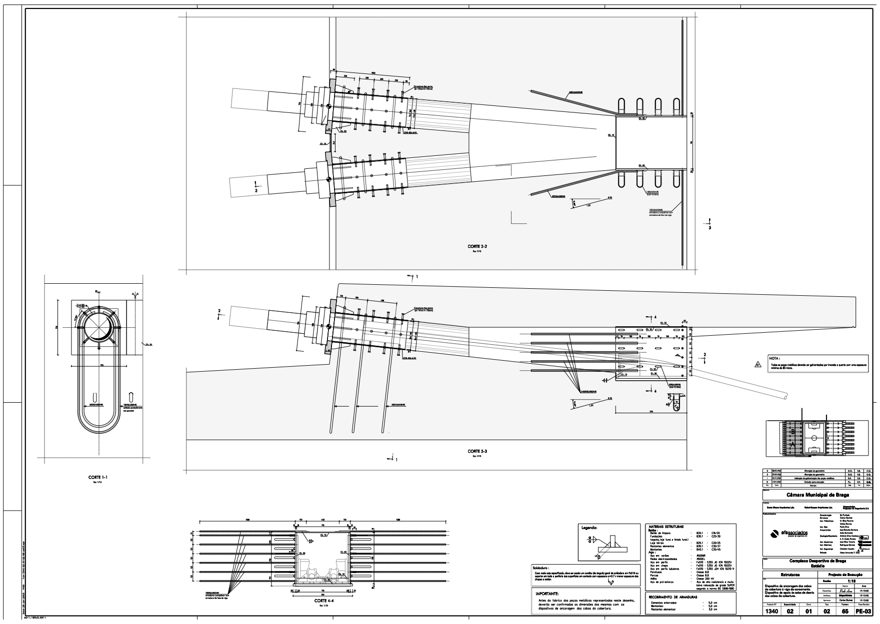
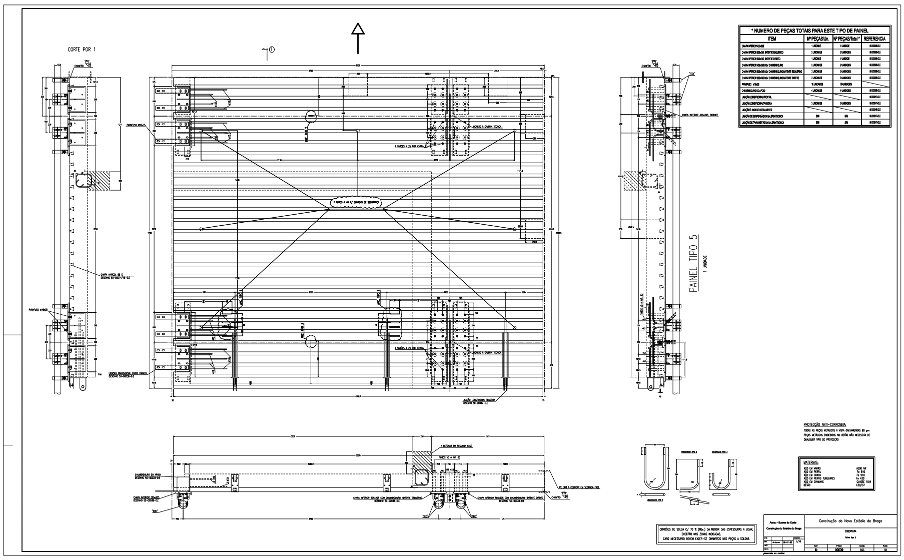
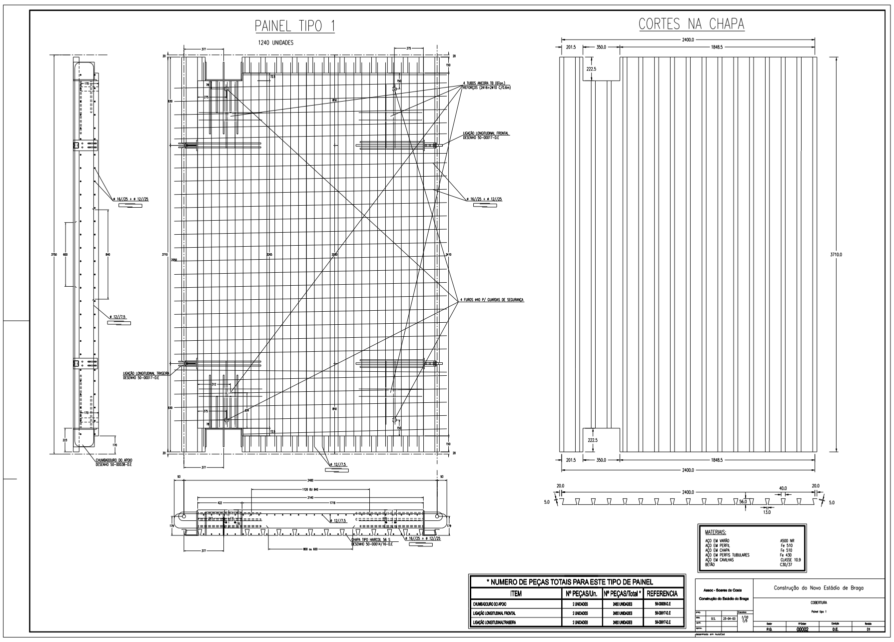
COBERTURA









PAINEL TIPO 1
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CORTES NA CHAPA
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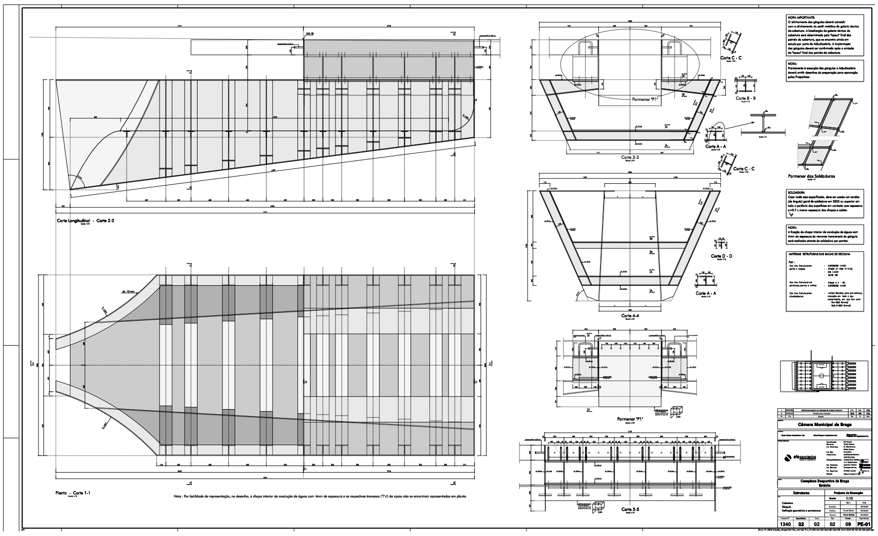

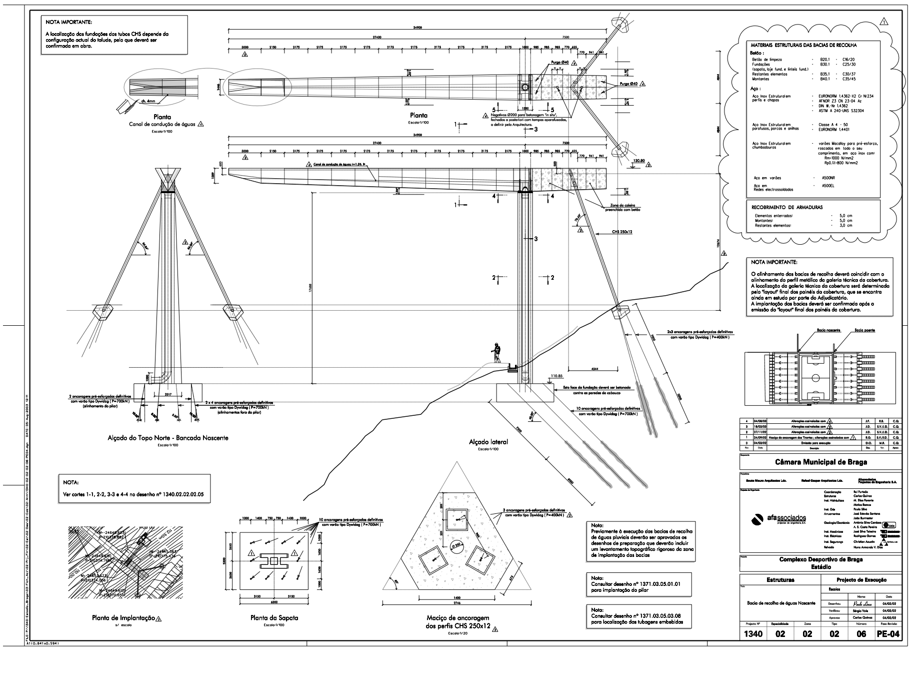

NOTA IMPORTANTE:
A localização das fundações dos tubos CHS depende da configuração actual do talude, pelo que deverá ser confirmada em obra.
Planta
Alçado do Topo Norte - Bancada Nascente
Alçado lateral
Planta de Implantação
Planta da Sapata
Maciço de ancoragem dos perfis CHS 250x12
Câmara Municipal de Braga
Complexo Desportivo de Braga
Estádio
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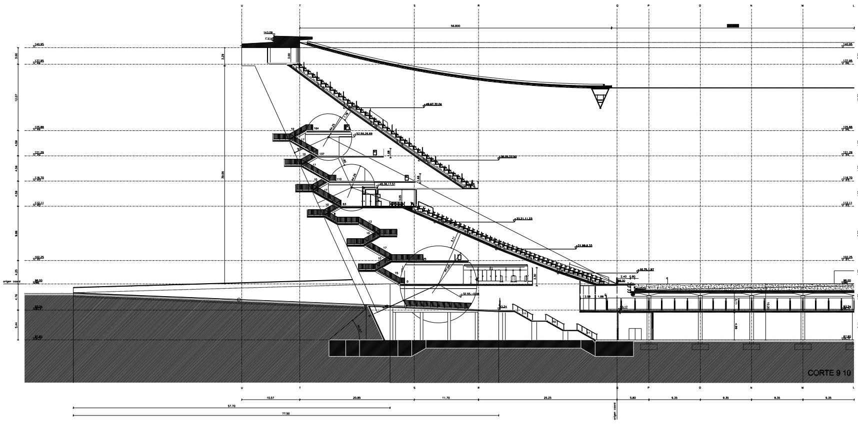
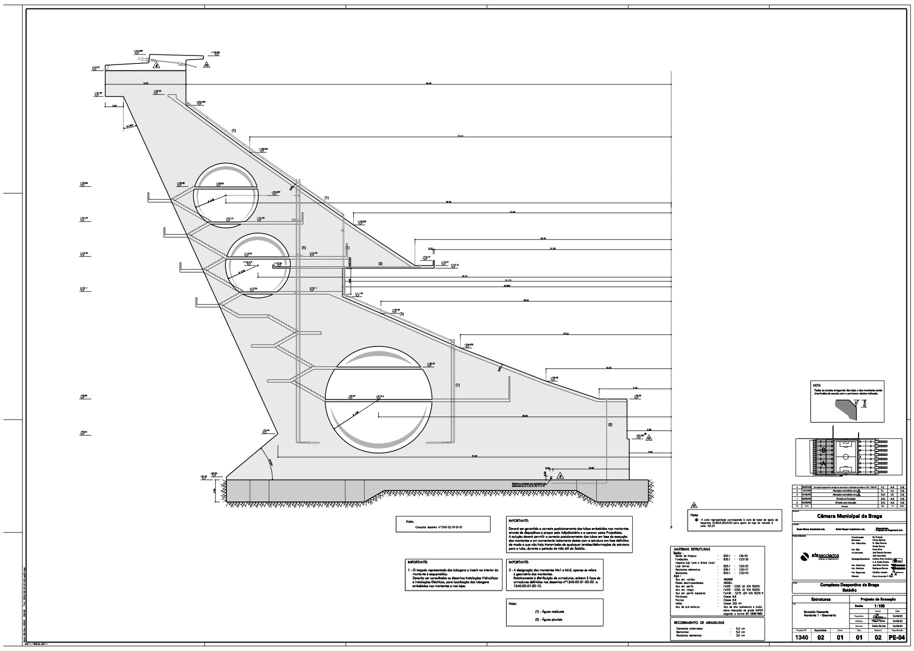
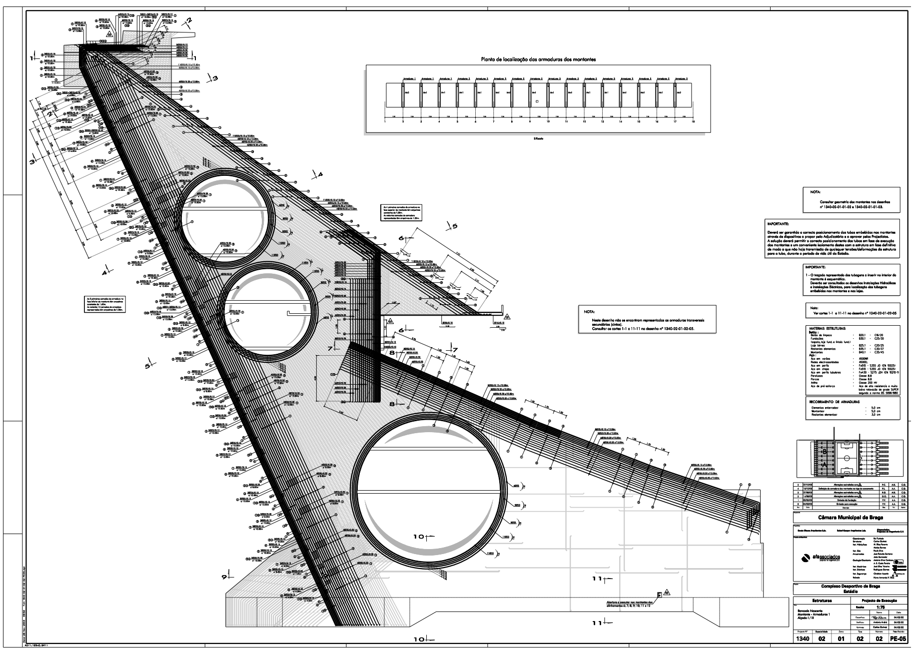
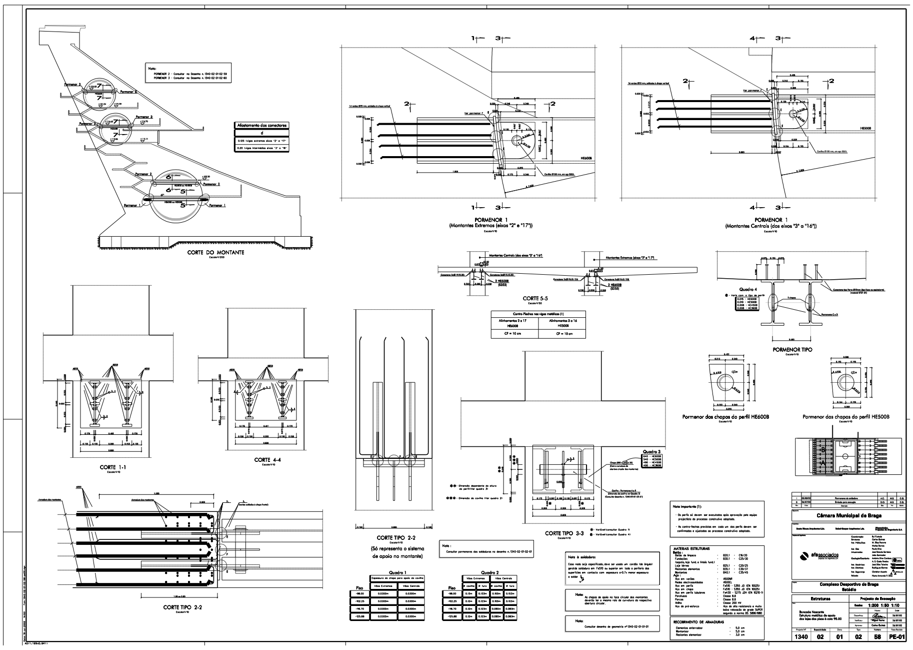
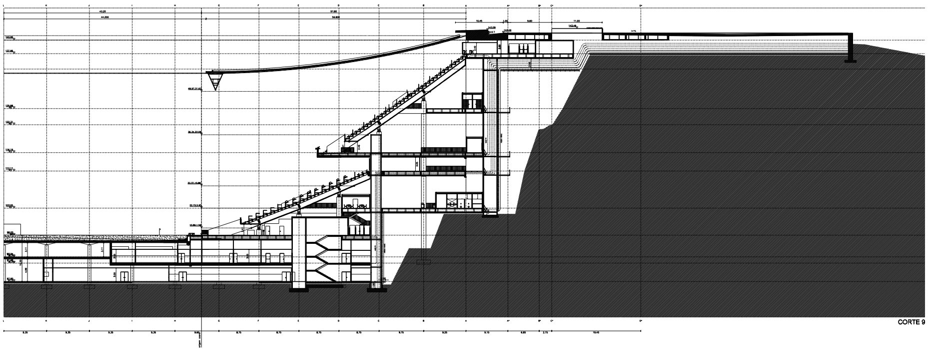
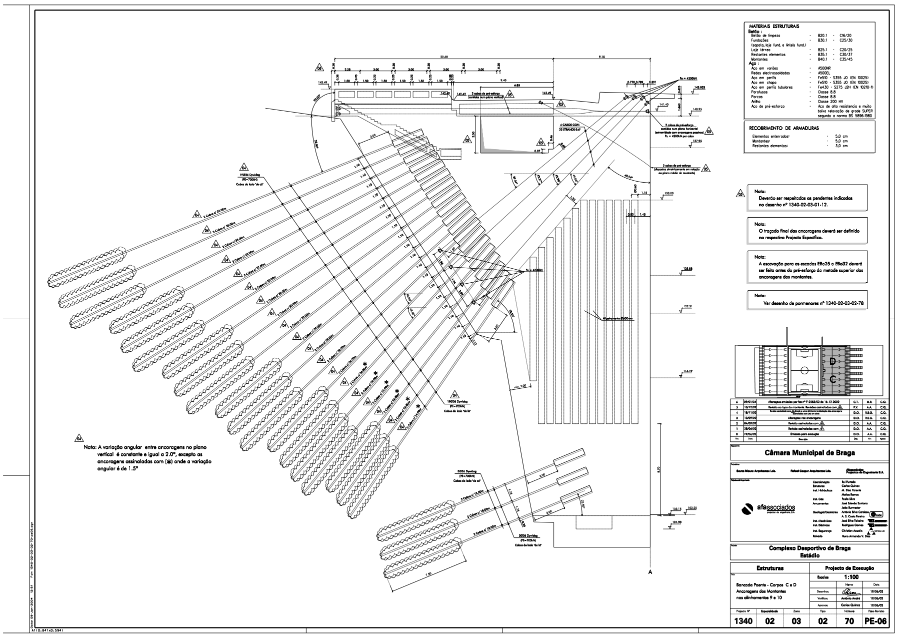

CORTE 9 10

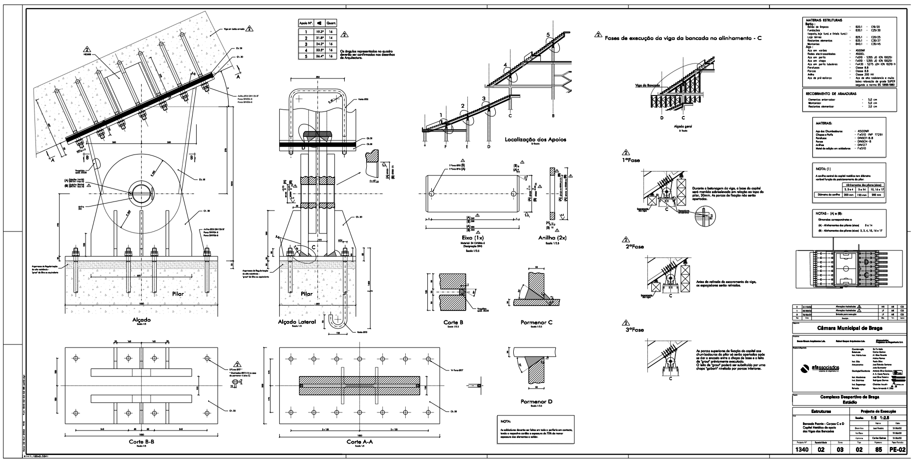

Câmara Municipal de Braga

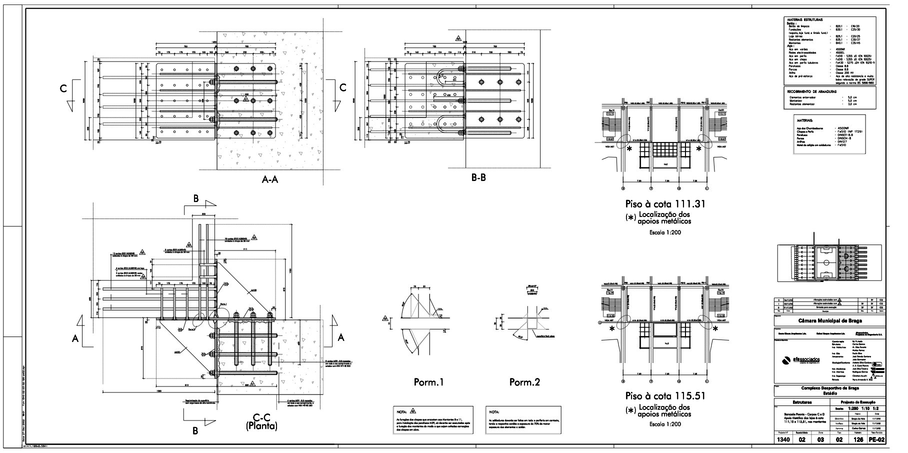

Planta de localização das armaduras dos montantes
Câmara Municipal de Braga

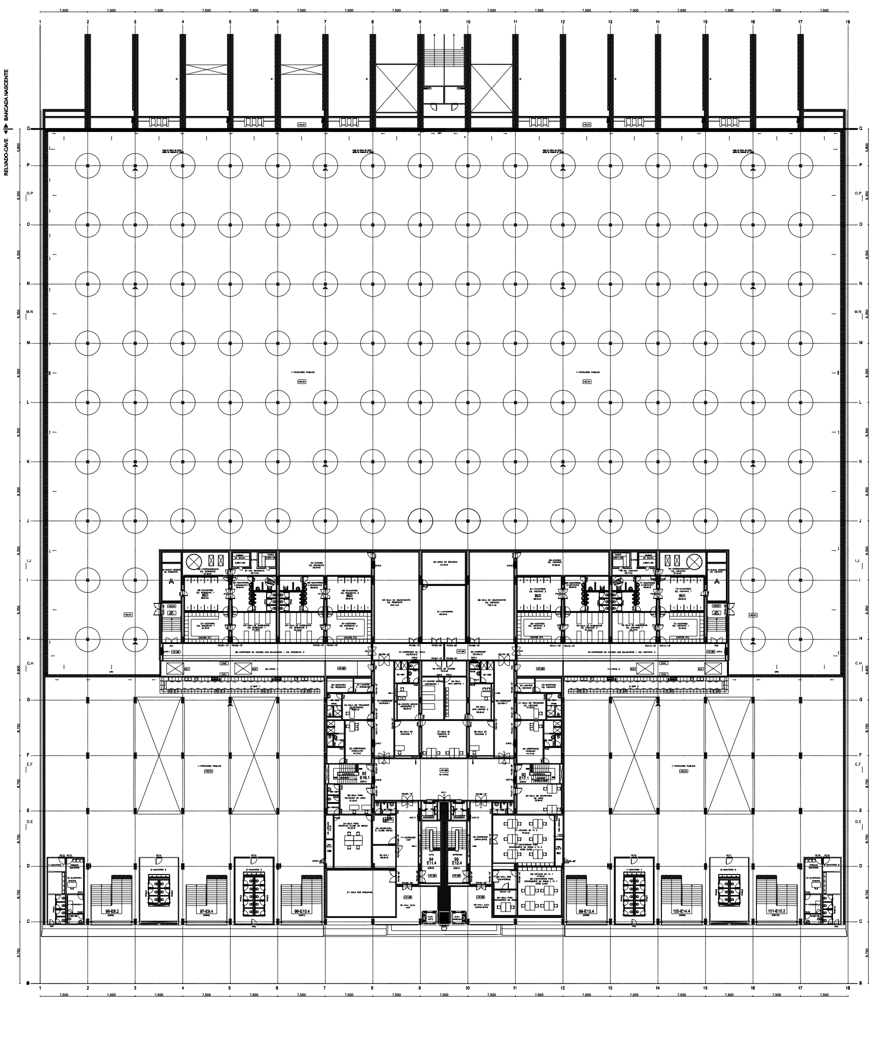

CORTE DO MONTANTE
CORTE 1-1
CORTE 4-4
CORTE TIPO 2-2
CORTE TIPO 2-2
CORTE TIPO 3-3
Câmara Municipal de Braga
PE-01

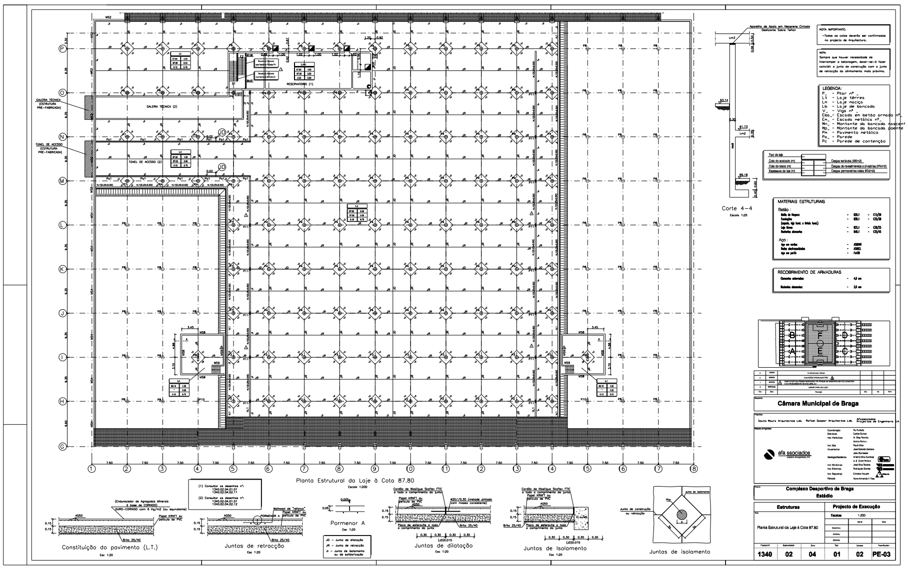

CORTE 9

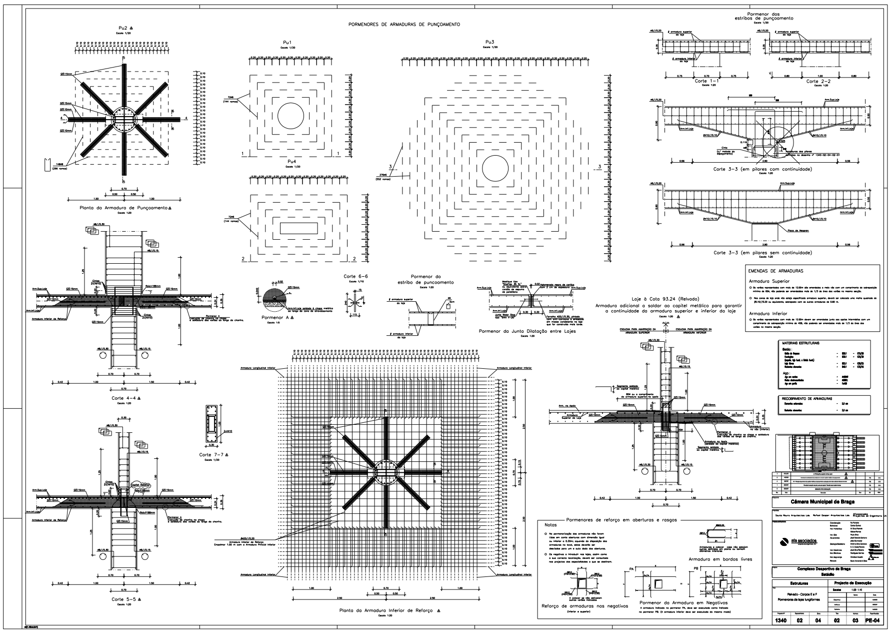

Câmara Municipal de Braga
Complexo Desportivo de Braga
Estádio
1:100
1340 02 03 02 70 PE-06


Alçado
Alçado Lateral
Pilar
Corte B-B
Corte A-A
Localização dos Apoios
Eixo (1x)
Anilha (2x)
Corte B
Pormenor C
Pormenor D
Fases de execução da viga da bancada no alinhamento - C
1ªFase
2ªFase
3ªFase
Câmara Municipal de Braga
Complexo Desportivo de Braga
Estádio
Estruturas
Projecto de Execução
1340 02 03 02 85 PE-02


A-A
B-B
C-C
(Planta)
Porm.1
Porm.2
Piso à cota 111.31
(*) Localização dos apoios metálicos
Escala 1/200
Piso à cota 115.51
(*) Localização dos apoios metálicos
Escala 1/200
Câmara Municipal de Braga
Complexo Desportivo de Braga
Estádio
1340 02 03 02 126 PE-02




Planta Estrutural da Laje à Cota 87.80
Constituição do pavimento (L.T.)
Juntas de retracção
Pormenor A
Juntas de dilatação
Juntas de Isolamento
Corte 4-4
Câmara Municipal de Braga
Complexo Desportivo de Braga
Estádio
PE-03


PORMENORES DE ARMADURAS DE PUNÇOAMENTO
Planta da Armadura de Punçoamento
Corte 4-4
Corte 5-5
Corte 7-7
Pormenor A
Corte 6-6
Pormenor do estribo de punçoamento
Pormenor da Junta Dilatação entre Lojes
Corte 1-1
Corte 2-2
Corte 3-3 (em pilares com continuidade)
Corte 3-3 (em pilares sem continuidade)
Planta da Armadura Inferior de Reforço
Reforço de armaduras nos negativos
Armadura em bordos livres
Câmara Municipal de Braga
Complexo Desportivo de Braga
Estádio
PE-04