

# Underground Parking structure built with deep foundations and vault precast elements in Spain

## *Aparcamiento subterráneo construido con cimentaciones profundas y elementos tipo bóveda prefabricados*

D. Fernández-Ordóñez <sup>(\*)</sup>, J. M. del Campo <sup>(\*)</sup>, J. C. Guerra <sup>(\*\*)</sup>, J. A. Ramírez <sup>(\*)</sup>

### SUMMARY

In many cases the only places available for the construction of a new car park are the existing streets or roads. These streets may also have important or historic buildings very close to the structure, which means that they cannot be disturbed in any way during the construction of the parking structure.

In this particular case, the novelty is that the top deck is solved with a unique structure: a vault that interacts with the pile wall not only for vertical but also for horizontal loads due to the arch mechanism. The construction of the vault is solved as a large precast element of one piece of more than 16 m in length and 2.40 m in width, which is built in the factory, transported with the help of trucks and erected on site with large cranes.

### RESUMEN

*En muchos casos las únicas localizaciones para construir aparcamientos son las calles o carreteras. Estas calles también suelen tener alrededor importantes edificios históricos muy cercanos a la propia estructura.*

*En este caso particular la novedad reside en que el forjado superior está resuelto con una estructura especial: una bóveda que interacciona con la pantalla de pilotes no solo en el sentido vertical sino también en el horizontal formando un verdadero mecanismo de arco. La construcción de la bóveda se ha resuelto con grandes elementos prefabricados de una pieza de más de 16 m de longitud y de 2,40 m de ancho. Se han fabricado en una factoría, transportados y montados en obra con grandes grúas.*

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**Keywords:** Underground parking structure; deep foundation; pile walls; erection sequence of structure; precast elements; vault structure.

**Palabras clave:** Aparcamiento subterráneo; cimentación profunda; pantalla de pilotes; secuencia de montaje; elementos prefabricados; bóveda.

<sup>(\*)</sup> EUITOP-Universidad Politécnica de Madrid (España).

<sup>(\*\*)</sup> FERROVIAL AGROMAN.

Persona de contacto/Corresponding author: david.fernandez-ordonez@upm.es (D. Fernández).

## 1. INTRODUCTION

Parking structures can be built both above and under ground. Parking structures built above ground are normally solved with a regular structure developed with columns, beams and slabs. When the situation does not allow enough land for a new structure above ground then new solutions have to be developed. This is a normally the case inside the cities in Spain where there is a great need for parking places but almost no place to build them (1) (2) (3).

In many cases the only places available for the construction of a new car park are the existing streets or roads. These streets may also have important or historic buildings very close to the structure, which means that they cannot be disturbed in any way during the construction of the parking structure (4).

A solution is then to build a pile wall in the first place to limit the deformations on the ground and to protect the buildings around and afterwards start building the rest of the structure (5).

Intermediate decks have to withstand normal loads for parking structures but the top deck has to endure traffic loads and also the land fill that is needed for landscape purposes of the street. These loads are quite large, normally higher than highway traffic loads or railroad loads (6).

In this particular case, the novelty is that the top deck is solved with a unique structure: a vault that interacts with the pile wall not only for vertical but also for horizontal loads due to the arch mechanism. The construction of the vault is solved as a large precast element of one piece of more than 16 m in length and 2.40 m in width, which is built in the factory, transported with the help of trucks and erected on site with large cranes.

After the vault for the top deck is built and secured, then excavation of the lower levels and the construction of the lower decks is developed.

This article describes the complete system of an underground parking structure built using the cut and cover method using pile walls, and special vault precast elements for the top deck, taking into account the soil interaction with the structure for both structural safety of the structure itself and also for the buildings around it (7).

The underground parking structure has an almost rectangular external perimeter of 108.50 x 17.20 m. The maximum depth

needed in order to get two parking levels, plus an important variable fill between 2.47 m in areas coinciding with the longitudinal pile walls and 0.52 m in the longitudinal axis of the parking area is approximately 25.8 m excavation. We take into account the depths of the two decks is a total height of excavation from the top deck level, and given that there will be a preliminary excavation of 0.50 m to configure the work platform, there will be an excavation for the pile wall of 7.75 m.

The construction system is planned descending: an excavation is first performed to the elevation of the working platform, situated 50 cm below the current street level, then the pile wall is built. In the next phase the excavation of the working platform, up to 2.57 m below the top of the beam that joins the piles pile wall, is carried out.

At this elevation the beam that joins all the piles will form the supporting base of the precast vaults that builds the deck. These segments have a span of 15.83 m, the longitudinal line is curved, so once placed, they form a dome with rotational symmetry. Once the deck is finished then the filling and urbanization are executed, while digging begins under the vaults to the height of maximum excavation that coincides with the level of support of the foundation slab. Finally, the internal structure of the parking structure, (slab foundation, columns and decks) is built.

Precise Geotechnical information has been used for the realization of this project, based on the Geotechnical Report by SAVIA to EUROCONSULT. This has been interpreted to characterize the soils in the study developed according to the experience with similar soils in Aranjuez, Spain.

The structural calculations were carried out by Grahen Ingenieros. and precast elements were partially checked by the Technical Department of Prefabricados Castelo. The design of the solution was carried out by architects Luis Agosti Sánchez Sánchez and Jorge Gomez. The main contractor of the works was FERROVIAL AGROMAN under the direction of Jose Luis Lovera.

## 2. GROUND TYPOLOGY

The stratigraphy gathered from the data of the Geotechnical Report has been used. The findings and recommendations have been interpreted and nearby surveys experience has also been implemented. The following types of soils have been defined, where levels have been modified to adapt to the reference of the project.

LEVEL 0 (above top level of piles beam):

Type: Artificial Filling  
 Density: 19.00 kN/m<sup>3</sup>  
 Internal friction angle: 29.0 °  
 Cohesion 0.0 tn/m<sup>2</sup>  
 Depth: 0.50 m from urbanization

LEVEL 1°:

Type: Silt  
 Density: 17.0 kN/m<sup>3</sup>  
 Internal friction angle: 29.0 °  
 Cohesion: 0.0 kN/m<sup>2</sup>  
 Depth: 1 m from the 0.00 level  
 Ballast Mod: 200,000 kN/m<sup>3</sup>

LEVEL 2°:

Type: Gravel  
 Density: 20.0 kN/m<sup>3</sup>  
 Internal friction angle: 35.0 °  
 Cohesion: 0.0 kN/m<sup>2</sup>  
 Depth: Unlimited  
 Ballast Mod: 40,000 kN/m<sup>3</sup>

According to that indicated in the geotechnical study it has been found that the water table lies at a depth -9.50 measured from the level of urbanization. Therefore this information is accurate only for the calculation of ultimate load of the pile wall.

Taking into account the ground analysis of the geotechnical report no chemical attack on concrete is expected. In any event, it is indicated that given the nature of soils from the geotechnical report the use of a concrete of the type IIa + Qa is recommended because there could be a weak chemical attack to concrete (type IIa + Qa environment) so the use of special cements is not necessary, but a high dosage of cement in the concrete has been used.

**3. FOUNDATIONS AND PERIMETER WALLS**

Continuous reinforced concrete pile walls are vertical walls made in spans of up to 7 metres in length and thicknesses between 0.45 and 1.50 metres, and depths of up to 70 m, and they offer a solution to excavation difficulties in urban areas or close to the water table level.

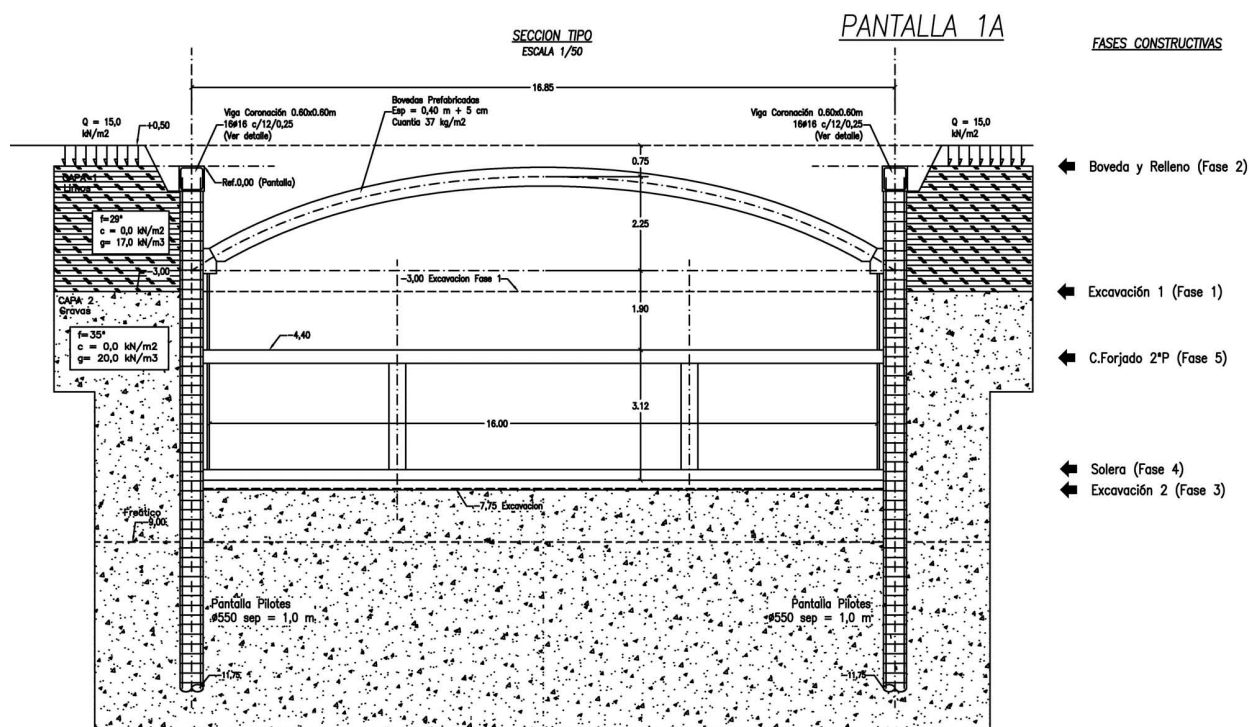
To install pile walls in the ground, mechanically-driven grab buckets are used with weight ratings of between 5 and 23 Tons and grab openings of between 2.60 and 4.20 metres. This type of grab bucket can be adapted to practically any type of soil and depth. To install pile walls on rocks, excavation techniques are used for thicknesses of 0.60, 0.80, 1.00 and 1.20 metres and depths of up to 60 metres (8) (9).

They are used in a large number of projects (bearing structures, provisional or definite retaining walls, etc.) and represent a solution for different problems such as the excavation of buried structures for example. underground car parks and basements, subways, etc. (10).

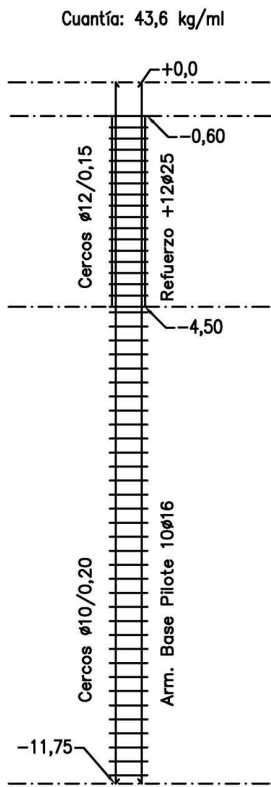
**Pile wall type 1, most common wall type**

The computer application reflects the above calculation of the pile wall according to how the construction process will in fact develop, because the result is not independent of it, due to the nonlinearity of soil behavior (Figure 1).

1. Pile wall type 1 Section. Configuration.



**ESQUEMA DE ARMADO**



Also relevant buildings are located close enough to generate important loads to affect the dimensioning of the pile wall do not exist in this section type (Figure 2). The foundations of the relevant existing buildings close to the site of the underground parking structure are footings at upper levels.

Additionally an overload of 15 kN/m<sup>2</sup> is set at pile wall top equivalent to the action of traffic and the weight of the land between the level 0.00 of calculation and the current urbanization level (+0.50 m).

**4. DESIGN CONSIDERATIONS FOR THE PILE WALLS**

ULS security has been checked for bending moments considering the compatibility with the axial force if this exists. With these moments the bearing capacity of the reinforcement has been checked. If the compression is of importance, steel strain is then calculated in each case, and real stress applies that may be less than the elastic limit. (Figures 3 ,4 and 5).

The structure is checked for the crack width of the sections, according to Article 49.2.4 of the EHE, (11) for the combination of SLS for frequent loads, which in the case of earth pressure coincides with the characteristic combination. This is initially estimated with mechanical homogenized characteristics of the section, and tensions in the materials considering that section. This checks whether the section is cracked or not, and the cracking moment and the steel stress at the time of cracking.

The calculation of stresses in the cracked section in service itself then follows. The mechanical characteristics of the cracked section and the stresses in all materials are

obtained thereafter. The steel will be used for the calculation of crack width. The characteristic crack width, then obtained, which for IIa + Qa environment should be less than 0.1 mm.

The shear strength is calculated in accordance with Article 44 of EHE. This is part of the maximum shear solicitations provided by the pile walls. From this VU1 (compression-shear limit shear) and Vu2 (sum of the collaboration of concrete and reinforcement) is calculated. In the whole process cracking in 45°, and vertical shear reinforcement are considered.

**5. STRUCTURE**

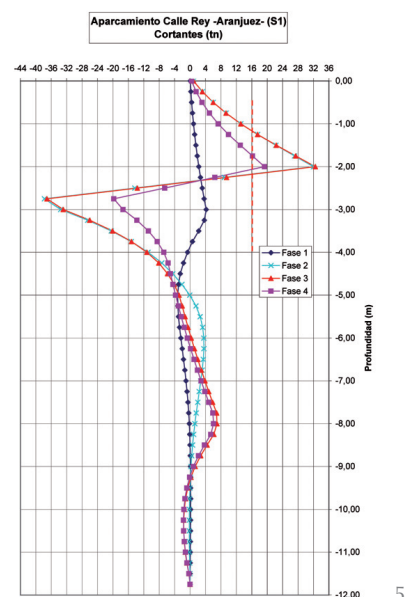
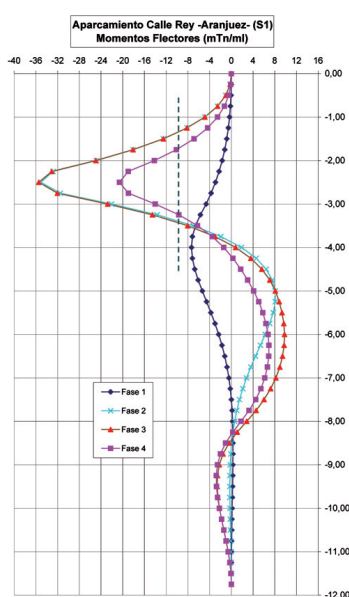
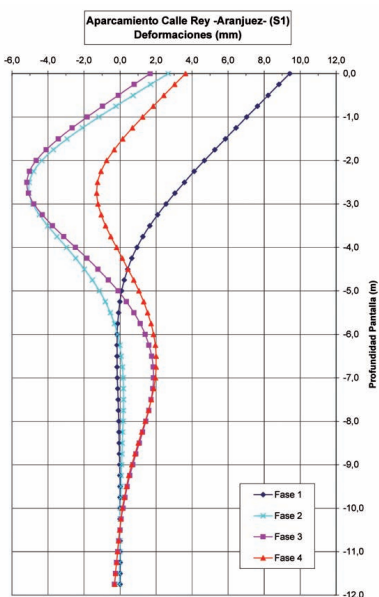
**5.1. Structure configuration**

The underground parking has two floors below the street above, with a longitudinal dimension of approximately 106 m and a 16.85 m transversally between pile walls. To this main body, a covered distributor is attached with irregularly shaped stairs and ramps that lead to the street. These necessary elements are built with traditional structure construction and according to the local normative on parking structures like the Madrid Community normative on accessibility (12) and the CTE (13).

The constructive conditions which determine the final typology that has been chosen are as follows:

- Provision of a large land fill on top of the deck that supports unrestricted planting of trees on the banks. This is a very important feature because it leads to lower earth filling in the center of the deck and more filling on the sides that allows planting.

2. Pile wall type 1 Section. Reinforcement
3. Deformations of pile wall type 1.
4. Bending Moments of pile wall type 1.
5. Shear in pile wall type 1.





- Downward construction to replace traffic on the top of the parking in the minimum time possible, much prior to the ending of the structure.
- Allowable stresses foundation available in the order of 50 kPa.
- Minimize execution time using precast elements

The structural typology used in this case is the provision of a recessed vault structure with a catenoid guideline, using the wall as a core system for the absorption of the important horizontal thrust required. The dome-shaped element permits to limit to a minimum the filling at the key (where is not needed for the planting of vegetation, with only 0.50 m), and instead it has more filling in the haunches up to 2.5 m of fill. The types used were as follows:

Pile perimeter retaining wall built with a series of piles, 55 cm in diameter, spaced 1.0 m and 4.0 m of embedment. It has an elevation of 7.75 m maximum digging height, starting from a level situated 0.00, 0.50 m below the street elevation. This allows a contention of curb filling on top of the deck without affecting pedestrian traffic or services. It also receives significant horizontal thrust of the vault at half height, with adequate rigidity to function through a beam chain connected to the pile wall. It has adequate bearing capacity to receive the vertical loads, not only by the resistance of the recessed area, but also by the frictional forces generated by the horizontal thrust

Vault made of prefabricated elements of 45 cm of depth and 2.40 m width, resting on the beams connected to the pile walls. The base span is 16.85 m for a camber of 2.25 m (relationship span/camber 7.5/1). The supports are considered articulated by delivering a hinge between the beam and the edge of the precast vaults. Key is left in a minimum cover of 0.50 m.

Intermediate deck made in situ with reticular recoverable elements of 20 +12, with 84 cm interval between nerve and minimum width of 16 cm, based on two columns longitudinally and alignments of 30 cm at its widest point, creating some spans in the vicinity of 7.0 m in the two main directions. Given the longitudinal dimension of parking, it was considered appropriate to introduce a transverse expansion joint dividing it into two separate modules.

For the pile walls it has been checked the security for ULS for bending moments considering the compatibility with the axial force if it exists. With these moments it has been checked the bearing capacity of the

reinforcement. If the compression is significant then is calculated steel strain in each case, and applies real stress that may be less than the elastic limit.

These detailed calculations of the behavior of the pile piles or walls are performed in different representative sections:

- Maximum negative bending moments in extrados
- Maximum positive bending moments at the base.

It is checked the crack width of the sections, according to Article 49.2.4 of the EHE, for the combination of SLS for frequent loads, which in the case of earth pressure coincides with the characteristic combination. This is initially estimated with mechanical homogenized characteristics of the section, and tensions in the materials considering that section. This checks if the section is cracked or not, and the cracking moment and the steel stress at the time of cracking.

Then follows the calculation of stresses in the cracked section in service itself. It is then obtained the mechanical characteristics of the cracked section and the stresses in all materials. The steel will be used for the calculation of crack width.

It is then obtained the characteristic crack width, which for IIa + Qa environment should be less than 0.1 mm.

The shear strength is calculated in accordance with Article 44 of EHE. This is part of the maximum shear solicitations provided by the pile walls. From this is calculated VU1 (compression-shear limit shear) and Vu2 (sum of the collaboration of concrete and reinforcement). In the whole process it is considered cracking in 45 °, and vertical shear reinforcement.

## 5.2. Building Materials and loads

According to the Spanish Standard EHE, the following general parameters are defined:

The exposure type of the structure is, for the concrete elements: IIa (non-marine exteriors-absence of chloride-exposed to the rain in areas of precipitation exceeds 600 mm/year). For the perimeter containment elements (piles) Qa. While it is true that the geotechnical report does not prescribe compulsory use of this type of concrete, it recommends its use, taking into account the nature of the soils identified.

The nominal and accidental cover (depending on the type of environment) is for the

elements in direct contact with the ground: 70 mm, for the other elements of foundation or (IIa): 25 + 10 mm and for the beams, Slabs and Walls (IIa): 25 + 10 mm. The safety coefficients are for normal control for concrete  $\gamma_c = 1.50$  and for steel  $\gamma_s = 1.15$

The types of concrete used are HA-30/F/20/IIa + Qa for the Pile walls, HA-40/S/20/IIa for the prefabricated Vault, HA-25/P/20/IIa for the foundations and HA-25/P/20/IIa for the structure, beams, slabs and walls. The concrete had the following properties of size of 20 mm maximum aggregate and a Modulus of Elasticity estimated for the calculation:  $E_c = 21.000 / 23.500 / 25000 \text{ N/mm}^2$ . The type of Steel for reinforcement is B 500 S for the entire work.

The structural typologies and Self Weight for the various decks of the parking structure are intermediate reticular decks with recoverable moulds depth-32 cm (20 +12), reinforced slab 40 cm of depth resting on the pile wall, interior walls and columns and precast concrete vaults of 45 cm depth and 2.40 m width.

The loads considered as Dead Loads are at the Intermediate Deck with a reticular slab 20 +12  $4.94 \text{ kN/m}^2$ , for the Top Level with a slab 0.40cm depth,  $10.00 \text{ kN/m}^2$  and for the Precast Vault of 0.45 m,  $11.25 \text{ kN/m}^2$ . The loads considered as Permanent Loads are at Intermediate Deck, Paving,  $0.50 \text{ kN/m}^2$ , at the Top Level, 20 cm + 30 cm floor  $10.60 \text{ kN/m}^2$ , and for the Precast Vault, 20cm pavement and earth fill that vary between 35 and 260cm. The density of the fill is considered  $18 \text{ kN/m}^3$  and the floor =  $4.80 \text{ kN/m}^2$ . The loads considered as Live Loads as CTE-SE-AE E IAP-98 (13) are at Intermediate Deck as a normal use as parking,  $4.00 \text{ kN/m}^2$  and at the Top Level, traffic loads with an uniform load of  $4.00 \text{ kN/m}^2$  and a 600 kN truck.

### 5.3. Precast Vault calculation

The calculation of the vault solution was made manually from the classical theory of strength of materials applied to two-hinged arches. The calculation is based on determining a horizontal thrust (H) in each load case as unknown indeterminate. The establishment of compatibility of deformations is done once a horizontal strain link is released. By application of Castigliano's theorem it is possible to calculate the deformation of the arch and the release of the force to reconcile movements. It is assumed that the supports are deformable horizontally to promote positive bending work of the vault. It works passively to the horizontal thrust, giving the pressure to ground through a beam connected to the pile wall and a biarticulated support of the vault.

The load cases developed for the load calculation were as follows:

- Self Weight and dead load, corresponding to the earth filling and paving, that generate variable loads in the haunches.
- Live load of  $4 \text{ kN/m}^2$  in the middle of the vault.
- Truck 600 kN at  $\frac{1}{4}$  span
- Truck 600 kN at  $\frac{1}{2}$  span
- Thermal and shrinkage deformation.

Truck point actions have been applied to a rectangular area equivalent to the footprint of truck (2 x 3) plus a widening of loads on the earth fill slope 1H / 2V in both directions, thereby establishing a rectangular area subjected to a uniform load.

For the thermal hypothesis has been a decrease of  $10^\circ \text{ C}$  and  $300 \mu\text{def}$  shrinkage according to site conditions and the type of concrete used.

That calculation is aimed to know well and with sufficient security bending work that may appear positive for the following circumstances:

- Deviation of the pressure on the antifunicular.
- Horizontal deformation of the pile walls.
- Point loads and antimetric loads.
- Shortening due to shrinkage and thermal deformation.

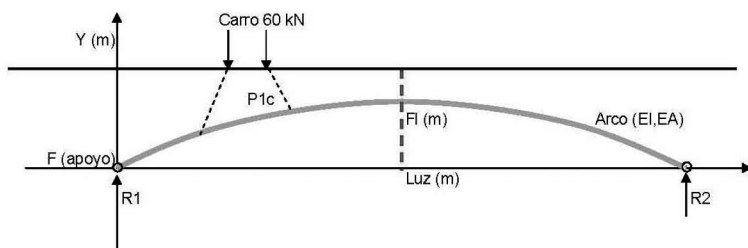
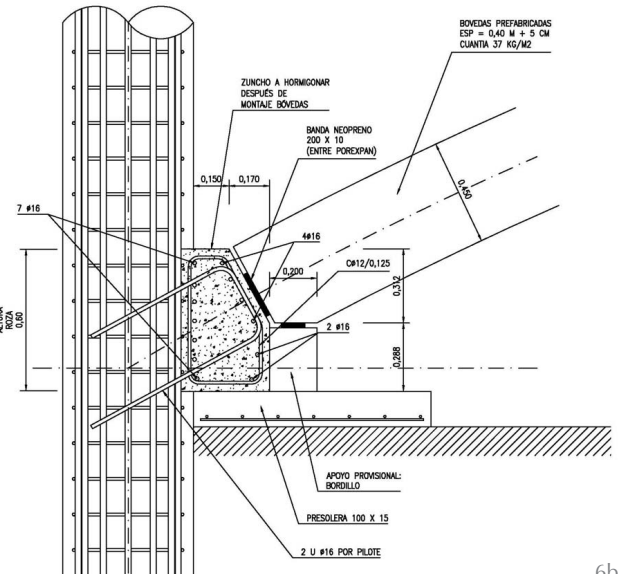
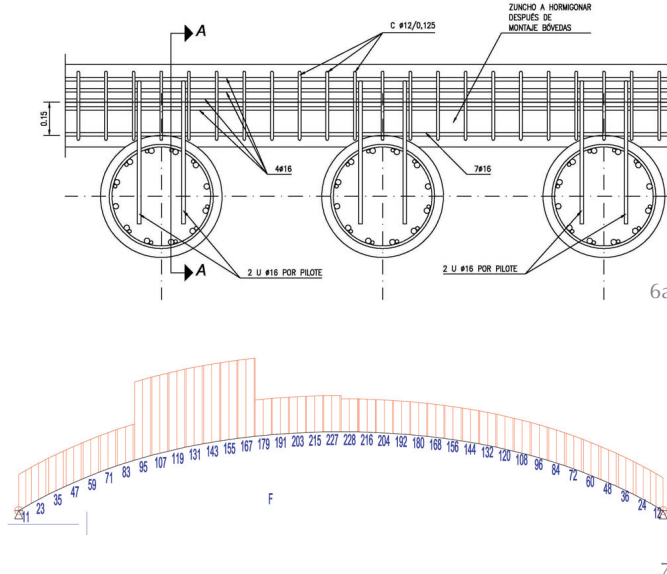
In order to minimize, the primary cause has been defined as a guideline for the vault antifunicular permanent loads (self weight and earth fill loads and pavement). The difference is relevant because it deviates up to 13 cm of the 2<sup>nd</sup> order Guideline.

It is also checked the compression and shear transfer between the vault and the pile walls in each different load case. Soil interaction in each case is considered.

The combination of ULS and SLS calculation is performed according to the criteria of IAP-98 and EHE-08, resulting in the combination of maximum positive bending moments, checking security in these circumstances. The frequent load combination is also checked for cracking and deformation, obtaining appropriate values for the calculated reinforcement (Figures 6, 7, 8 and 9).

To summarize the results we mention the following:

- Maximum positive bending moment (at Key):  $454.8 \text{ m kN/ml}$ .
- Compatible Axile force (Key):  $928.3 \text{ kN/ml}$ .



X <sub>i</sub> (m)	Y <sub>i</sub> (m)	Alfa <sub>i</sub> (r)	P <sub>i</sub> (kN)	P <sub>i</sub> X <sub>i</sub> (mkN)	Vox (kN)	Mox (mkN)	D <sub>s</sub> (m)	y2.D <sub>s</sub> (m3)	(m3kN) Solicitaciones arco			
									Mo.y.D <sub>s</sub>	Mx (mkN)	Vx (kN)	Nx (kN)
0.00	0.00	0.63	0.0	0.0	115	0			6.44	0.0	13.3	175.2
0.42	0.27	0.61	0.0	0.0	115	48	0.499	0.036	23.99	12.7	18.3	174.8
0.84	0.51	0.55	0.0	0.0	115	97	0.486	0.127	50.42	28.5	27.9	173.5
1.26	0.73	0.50	0.0	0.0	115	145	0.476	0.255	84.00	47.4	36.7	171.9
1.69	0.93	0.45	0.0	0.0	115	193	0.467	0.405	123.35	69.0	44.7	170.0
2.11	1.11	0.41	0.0	0.0	115	241	0.459	0.569	167.37	93.0	52.0	167.9
2.53	1.28	0.37	10.7	27.1	115	290	0.452	0.738	212.27	119.5	58.6	165.6
2.95	1.43	0.33	21.5	63.3	104	333	0.446	0.908	253.46	143.5	54.6	159.8
3.37	1.56	0.30	21.5	72.4	82	368	0.442	1.073	289.12	160.5	39.6	151.5
3.79	1.68	0.27	21.5	81.4	61	394	0.438	1.231	317.81	170.4	23.7	144.5
4.21	1.78	0.24	21.5	90.5	39	410	0.434	1.381	338.38	173.0	7.2	138.7
4.63	1.88	0.21	21.5	99.5	18	418	0.431	1.519	349.92	168.1	-9.8	134.0
5.06	1.96	0.18	21.5	108.5	-3	417	0.429	1.645	351.78	155.8	-27.4	130.4
5.48	2.03	0.16	10.7	58.8	-25	406	0.427	1.757	347.48	135.9	-45.2	127.7
5.90	2.09	0.13	0.0	0.0	-36	391	0.426	1.856	332.84	112.8	-52.8	127.4
6.32	2.14	0.11	0.0	0.0	-36	376	0.424	1.940	311.56	91.1	-49.8	128.6
6.74	2.18	0.09	0.0	0.0	-36	361	0.423	2.010	298.89	70.7	-46.9	129.7
7.16	2.21	0.06	0.0	0.0	-36	346	0.422	2.064	285.09	51.5	-44.0	130.7
7.58	2.23	0.04	0.0	0.0	-36	331	0.422	2.102	270.31	33.5	-41.2	131.6
8.00	2.25	0.02	0.0	0.0	-36	316	0.421	2.125		16.7	-38.5	132.4
8.43	2.25	0.00	0.0	0.0	-36	301	0.421	2.133		1.1	-35.7	133.2
8.85	2.25	-0.02	0.0	0.0	-36	286	0.421	2.124		-13.4	-32.9	133.9

- Maximum vertical characteristic reaction: 437.2 kN/ml.
- Maximum horizontal characteristic reaction: 679.4 kN/ml.
- Deformation in frequent combination (key): 9.6 mm.

**5.4. Precast vault construction in the factory**

Vault elements have been made precast in the factory of Prefabricados Castelo, about 20 Km away. The elements are 16m long, measured in the cord, 2.40m wide, and 0.45m thick. The weight of the elements is 44.1 tons which gives an idea of the difficulty for production and later transport and erection. The elements have been concreted in a

vertical way, 90° from the final position on site due to process needs. The moulds have been designed as a whole to resist fresh concrete forces with very low deformation. Self compacting concrete has been used to assure perfect filling of the forms and finishing of the surfaces (Figure 10).

The reinforcing cage, that weighs 1600 Kg, is built as a whole and then placed into the mould, that has been specially designed for this work. For transport and erection needs, a double set of lifting devices have to be placed in the elements, 8 for lifting in the vertical way in the factory and another 8 to be used in the final position and erection (Figures 11 and 12).

6. Support of the vault in the pile walls. Longitudinal and cross section.

7. Example of load distribution with eccentric loads.

8. Bending moments and Shear in the Vault due to eccentric point loads.



9. Combination of forces and moments in the Vault.

**COMBINACIÓN**

Coef. Mayoración Indirectas = 1.22

10. Workshop drawing of form definition of the normal precast segments.

11. Workshop drawing of reinforcing.

12. Mould and reinforcing cage.

13. Movement of elements in the factory.

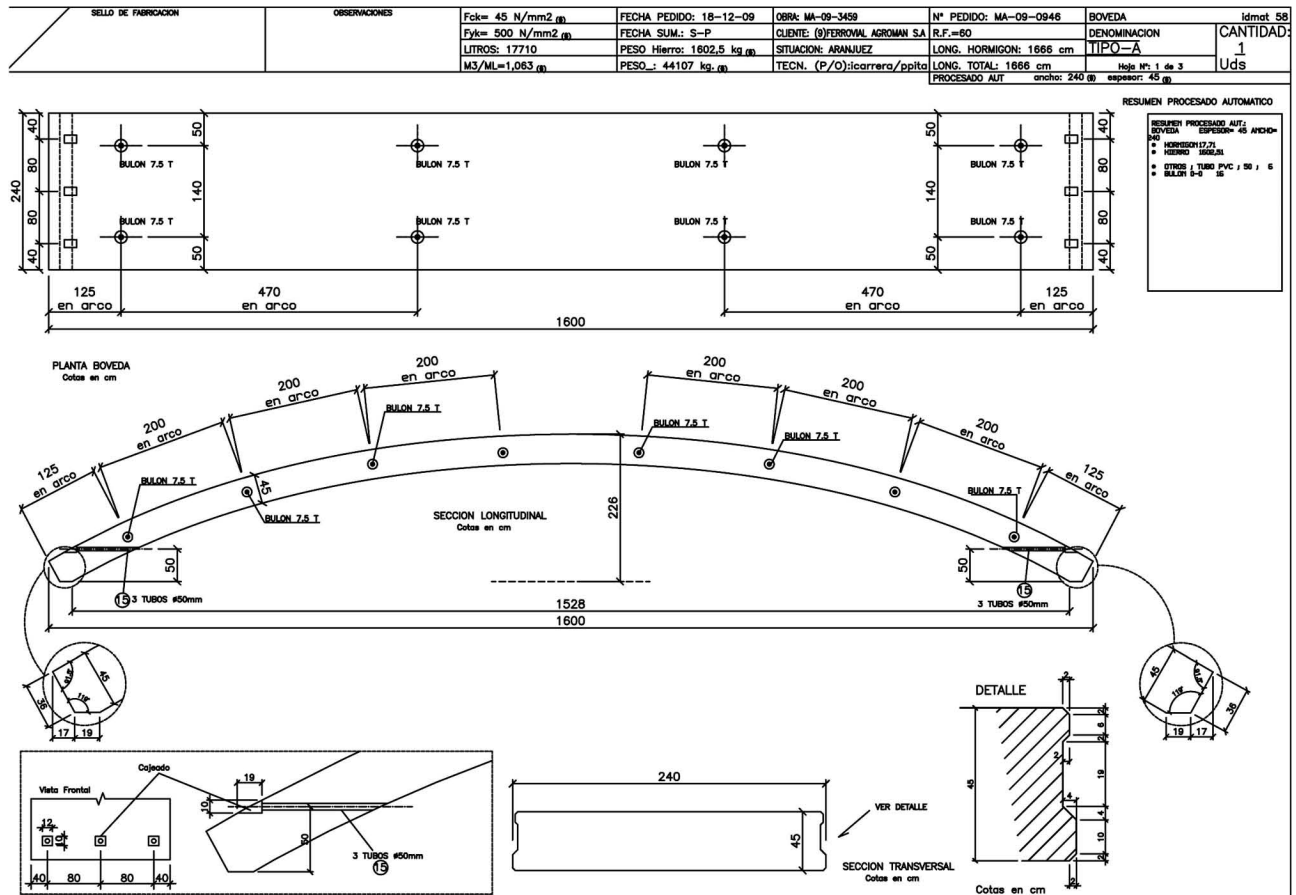
14. Transportation with special trucks.

15. Work site just after construction of pile walls and before erection of vault elements.

X <sub>i</sub> (m)	Momento Max (+) Carros			Momento Max (-) Carros			Combinación ELU Flexión (+)			Combinación ELS Frecuente		
	Mx (mkN)	Vx (kN)	Nx (kN)	Mx (mkN)	Vx (kN)	Nx (kN)	Md (mkN)	Vd (kN)	Nd (kN)	Md (mkN)	Vd (kN)	Nd (kN)
0.00	0.0	13.3	175.2	0.0	-62.1	230.5	0.0	26.0	961.4	0.0	-0.1	600.3
0.42	12.7	18.3	174.8	-23.0	-55.5	232.2	43.3	48.4	948.8	16.6	9.3	606.0
0.84	28.5	27.9	173.5	-40.6	-42.6	234.9	89.6	69.8	925.8	34.0	19.9	591.4
1.26	47.4	36.7	171.9	-53.2	-30.7	236.7	138.5	87.3	905.0	52.0	28.3	578.4
1.69	69.0	44.7	170.0	-61.3	-19.6	237.9	189.8	101.6	886.4	70.7	34.9	567.0
2.11	93.0	52.0	167.9	-65.2	-9.3	238.5	243.1	113.4	869.6	90.0	40.1	556.9
2.53	119.5	58.6	165.6	-65.2	0.3	238.7	298.3	123.1	854.7	109.7	44.2	548.1
2.95	143.5	54.6	159.8	-61.6	9.2	238.5	348.3	115.8	836.0	127.5	42.3	538.6
3.37	160.5	39.6	151.5	-54.6	17.4	238.1	386.3	91.4	815.1	141.2	34.5	528.9
3.79	170.4	23.7	144.5	-44.5	25.1	237.4	411.9	65.3	797.5	150.7	26.0	520.7
4.21	173.0	7.2	138.7	-31.5	32.3	236.5	425.1	37.9	782.7	156.0	16.8	513.7
4.63	168.1	-9.8	134.0	-15.7	39.0	235.5	425.7	9.4	770.7	156.9	7.3	508.0
5.06	155.8	-27.4	130.4	0.0	0.0	0.0	413.6	-20.0	761.0	153.5	-2.6	503.4
5.48	135.9	-45.2	127.7	0.0	0.0	0.0	388.7	-50.1	753.5	145.8	-12.8	499.7
5.90	112.8	-52.8	127.4	0.0	0.0	0.0	357.7	-64.6	750.2	136.0	-17.9	497.6
6.32	91.1	-49.8	128.6	0.0	0.0	0.0	327.4	-63.5	749.7	126.2	-17.7	496.6
6.74	99.4	67.4	229.0	0.0	0.0	0.0	340.6	109.1	898.5	131.0	39.6	545.6
7.16	129.0	72.4	227.4	0.0	0.0	0.0	384.4	113.2	895.0	145.8	40.8	543.9
7.58	154.5	62.8	225.2	0.0	0.0	0.0	422.2	84.6	933.5	158.6	31.1	542.1
8.00	169.8	38.7	223.3	0.0	0.0	0.0	446.7	44.2	929.9	166.9	17.4	540.6
8.43	174.9	14.4	222.4	0.0	0.0	0.0	454.8	5.0	928.3	169.6	4.2	540.0
8.85	169.8	-38.7	223.3	-13.4	-32.9	133.9	446.7	-87.2	929.9	166.9	-31.7	540.6
9.27	154.5	-62.8	225.2	-26.7	-30.1	134.6	422.2	-122.5	933.5	158.6	-43.7	542.1
9.69	129.0	-72.4	227.4	-38.8	-27.2	135.2	384.4	-126.1	895.0	145.8	-45.1	529.9
10.11	99.4	-67.4	229.0	-49.6	-24.3	135.7	340.6	-118.8	898.5	131.0	-42.8	531.6
10.53	71.9	-62.3	230.4	-59.3	-21.2	136.3	298.6	-111.2	902.5	116.6	-40.5	533.5
10.95	46.6	-56.9	231.8	-67.6	-18.0	136.7	258.4	-103.4	908.8	102.8	-38.1	535.7
11.37	23.4	-51.2	233.1	-74.7	-14.7	137.1	220.1	-95.3	911.6	89.6	-35.6	538.2
11.80	2.6	-45.3	234.4	-80.3	-11.2	137.4	183.9	-86.7	916.9	76.9	-32.9	541.0
12.22	0.0	0.0	0.0	-84.5	-7.5	137.7	173.5	-19.3	969.6	72.8	-10.6	426.4
12.64	0.0	0.0	0.0	-87.1	-3.6	137.9	165.6	-19.8	974.6	69.5	-10.8	429.6
13.06	0.0	0.0	0.0	-88.1	0.6	137.9	156.3	-20.3	980.7	65.5	-11.0	433.4
13.48	0.0	0.0	0.0	-87.3	5.1	137.8	145.4	-20.7	987.8	61.0	-10.9	437.8
13.90	0.0	0.0	0.0	-84.7	9.8	137.5	133.0	-20.9	996.3	55.8	-10.7	443.1
14.32	0.0	0.0	0.0	-80.0	14.9	137.1	119.1	-20.9	1006.2	49.9	-10.2	449.3
14.74	0.0	0.0	0.0	-73.2	20.4	136.4	103.5	-20.5	1017.8	43.4	-9.2	456.6
15.17	0.0	0.0	0.0	-64.0	26.3	135.4	86.3	-19.4	1031.4	36.3	-7.5	465.1
15.59	0.0	0.0	0.0	-53.2	30.7	236.7	67.4	-17.4	1047.3	28.4	-5.0	475.1
16.01	0.0	0.0	0.0	-40.6	42.6	234.9	46.8	-14.1	1065.6	19.7	-1.3	486.7
16.43	0.0	0.0	0.0	-23.0	55.5	232.2	24.3	-8.9	1086.7	10.3	3.9	500.1
16.85	0.0	62.1	230.5	0.0	-13.3	175.2	0.0	76.2	1044.2	0.0	34.2	646.8

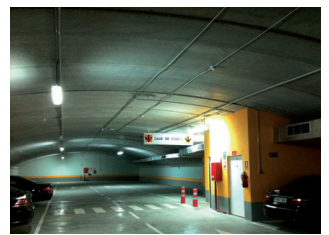
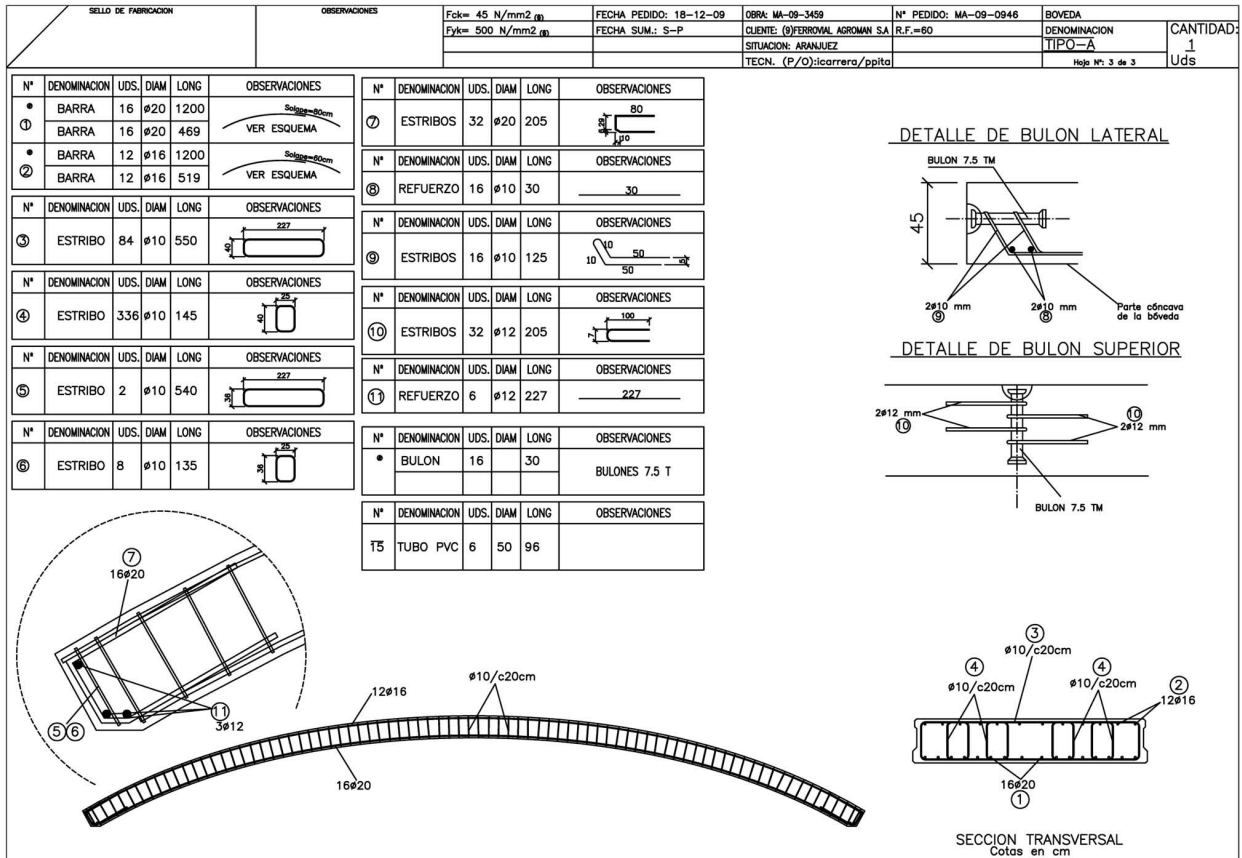
Hk max (kN/m) = 679.4 Reacción Horizontal máxima característica sobre pantalla  
 Hk.frec (kN/m) = 457.0 Reacción Horizontal combinación frecuente  
 Vk .max (kN/m) = 437.2 Reacción Vertical máxima característica sobre pantalla

9



10





Because the elements have been concreted in a vertical way the elements have to be tilted to the final horizontal way. The tilting has to be done in the factory with the help of large mobile cranes (Figure 13).

For the temporary work as a vault when the elements are in horizontal way, during stock, transport and erection some tension bars have been designed to resist the horizontal force due to the arch behavior for self weight. These tension elements have to be adjustable and removable after the concrete has been finished on site, when the vaults work as they are designed. The tension elements are 3 bars of diameter 32 mm for each vault element (Figure 14).

### 5.5. Precast vault transport and erection

For transportation special trucks were used; one vault element in each truck. All the elements had to have tensile bars to be able to resist the horizontal load that comes from the vault action on self weight. Erection was made with a large mobile hydraulic crane. Due to the limited space available on site it was necessary to complete erection with just one crane instead of two which would have given more flexibility (Figures 15 and 16).

The vaults are temporarily supported on vertical footings on the ground that is excavated just at the level of the support. After the concrete placement of the connection

16. Erection of vault elements with a single crane on top of the distribution beam of the pile wall.

17. Vault elements already erected in the final place of the structure just before excavating next levels.

18. Final state of the outside of the parking structure with trees and other urban elements.

19. Final state of the inside of the parking structure with box for the stairs.

of the vault and the pile wall the temporary footings are released and thus the vault loads on the pile walls.

After the erection of the vault elements then the connection with the pile wall is concreted and then the excavation can continue because the vault structure acts as a prop to the horizontal forces coming from the pile walls. Then both the street circulation and garden planting can be finished straight away so as to inconvenience as little as possible the users of the streets (Figure 17).

The final view of the street with the trees and other urban elements well integrated in the urban landscape can be seen in Figure 18. Also it is possible to see the final view of the parking structure from the inside (Figure 19). In this picture it is possible to see the installations for ventilation and for electrical equipment integrated in the design and also the places for the stairs combined in the vault design.

## 6. CONCLUSIONS

For parking structures, when the situation does not provide enough land for a new structure above ground then new solutions have to be developed. This is normally the case inside the cities in Spain where there is an important need for parking places but almost no place to build them. The following ideas can be set as conclusions:

1. In many cases the only places where it is possible to be able to build a new parking are the existing streets or roads.

2. These streets also have important or historic buildings, very close to the structure, which cannot be disturbed in any way during the construction of the parking structure.
3. A solution is then to build a pile wall in the first place to limit the deformations on the ground and to protect the surrounding buildings and afterwards start building the rest of the structure.
4. Intermediate decks have to resist normal loads for parking structures but the top deck has to resist traffic loads and also the land fill that is needed for garden purposes of the street. These loads are quite large, normally higher than highway traffic loads or railroad loads.
5. In this special case the top deck is solved with a very special structure, a vault that interacts with the pile wall not only for vertical but also for horizontal loads due to the arch mechanism, taking into account the soil interaction with the structure for both structural safety of the structure itself and also for the surrounding buildings.
6. The construction of the vault is solved as a large precast element of one piece of more than 16 m in length and 2.40m in width which is built in the factory, transported with the help of special trucks and erected on site with large cranes.
7. After the vault for the top deck is built and secured then excavation of the lower levels and the construction of the lower decks are developed.

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