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Lightweight structures, heavy foundations?

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Abstract

It is well known that most of tensile structures foundations are made with concrete footings. Not because it is the best form to solve this part of the structure, but because it is the easiest way for many builders-manufacturers. And it is not a surprise either, the comments about the big size of these footings.

It is also curious, at least, the absence of regular bibliography about tensile structure foundations. Although we can find some special texts (PhD Theses, papers…), it's not so easy to find regular books about them.

A serious approach to this subject must consider the different types of typical actions[1] arriving or demanding these foundations (footings). Pushing forces (vertical or inclined), pulling forces (vertical or inclined) and moments without vertical force are the most common situations we must face.

But not only actions are different. Lightweight structures foundations behave quite differently from regular foundations in regular buildings. The importance of the settlements (the importance of the lower soil layers), the horizontal resistance of soil, the situation and size-form of the reinforcement, etc. are concepts that must be revised since they can be completely different.

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In this paper, a complete catalog of situations and solutions are studied and proposed for most of all the situations we can find in this type of foundations.

Main discussion is placed about horizontal resistance and overturning resistance. These are probably the maximum difference between this type of foundations and regular ones. But we cannot forget about rain protection, soil-concrete friction, existence of pavement slab, etc., since these aspects can be crucial in the lightweight structures foundations design and absolutely negligible in most of regular building foundations.

If reinforced concrete is used (as it happens most of the time) position and evaluation of the reinforcement are key elements to be taken into account. Exactly the same about pulling elements and their anchorages to the footing.

This paper pretends to fill succinctly a gap in the footing foundation design procedure, so well covered in regular building bibliography.

Keywords: foundations, passive earth pressure, cohesion, soil friction, footing, anchorage

1. Foundations of tensile buildings

Foundations of traditional buildings (structures of stone, brick, wood, steel, etc.) are very different. Depending on the type of soil, its stratification, the type of the structure (frames, continuous…) and the type and magnitude of loads, a typology of diverse foundations is generated: isolated, strip, off-centre footings; foundation beams and slabs; piles, etc.

However, despite this diversity, often a common factor is found. The predominant load on the foundation is compression. A force pushing down the foundation and must be countered by the resistance of the soil beneath the foundation (or next to it, friction, in some types such as certain piles).

It is true that we also can find other cases with other types of loads; especially in structures with columns built in the foundations (at least this is the usual way to calculate the structures). These columns have at its bottom shear forces and bending moments that have to be balanced. Shear forces are usually not very important and, therefore, in most cases the problem is solved with the tensile or compression resistance offered by horizontal braces that are arranged between different footings.

As for the bending moment, it may be important at the border columns of frames and especially in the off-centre footings (for example, under border walls). In these cases solutions are diverse, but often strap beams between this footing and the next one inwards is the most usual solution.

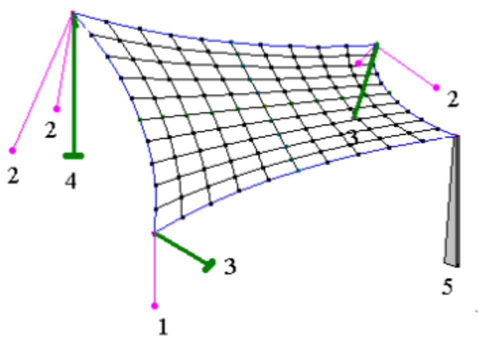
Even so, in all these cases, vertical load of compression is the most important load and the one which determines the type of foundation to use.

In tensile buildings we can also find foundations like those just discussed, for example, in the central vertical mast of a conoid-shaped roof, but these cases are less frequent.

2. Typology of Foundations

In general, foundations of typical tensile buildings can be classified depending on the load to be resisted, in any of these types:

1. Vertical pulling load (vertical cable)
2. Leaning pulling load (any cable or guy-rope fixed to the ground)
3. Leaning pushing load (tilted masts, base of an arch, etc.).
4. Vertical pushing load (vertical mast)
5. Bending moment, with vertical and horizontal loads of lesser importance (especially vertical columns supporting a membrane, without stays or guy-ropes)

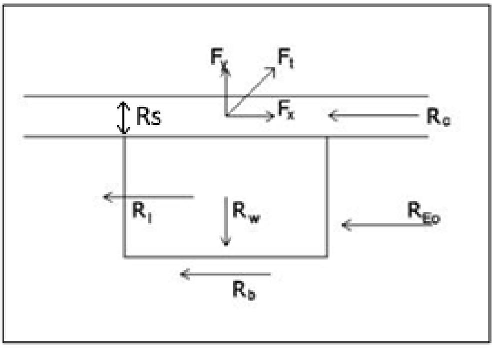


As we can see, only type 4 is what we would call traditional foundation. Type 3 could be considered traditional if the horizontal component was very small or if it was possible to establish a grid of straps between these and other footings. If not, we'll see that the design of the foundation is quite different.

2.1. Balance resources

To balance the loads produced by the structural elements of the tensile constructions, foundations use a different set of resources that, although they could be used in any type of foundation, are more common in this typology.

So, we can consider the following resources:



The compressive strength of the soil at the bottom of the foundation.
The compressive strength of the soil, at the sides of the foundation.
The friction between the sides and the bottom of the foundation with the soil.
The weight of the foundation and all other materials or structural elements located above the foundation: soil, base, slab, pavement …
The mechanical resistance of a possible continuous reinforced concrete slab, on the foundation.

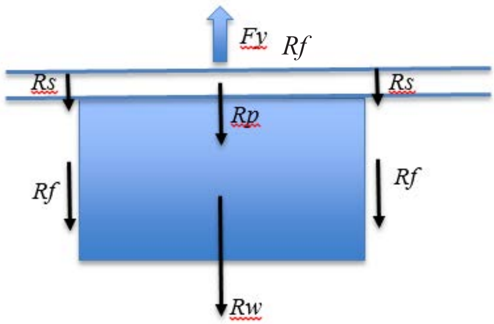
3. Study of cases

If we accept that tensile structures foundations can be classified in these five categories, now we can consider each one in an independent analysis. This analysis can be very extensive [1] but in this paper we will just introduce the main points to be considered.

3.1 Vertical pulling load

This is the simplest case. The foundation is subject to the vertical pulling load F_y. To provide stability, the foundation will resist this force in several ways:

- R_w by its own weight
- R_p by the weight of the pavement that may exist on the foundation
- R_f by the lateral friction against the ground
- R_s by the shear strength by the slab of pavement, if any



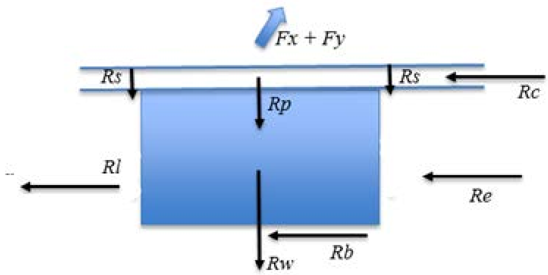
3.2 Inclined pulling load

In this case pulling force F_t has two components vertical F_y and horizontal F_x. F_y has already been studied in the previous section (although it will be re-studied later on when considering footing rotation). Now we will pay attention to the behaviour of F_x .

In order to guarantee stability the footing will put up resistance to F_x in some different ways.

- R_e soil lateral resistance. produced by lateral earth pressure E_0 (passive earth pressure E_p could be used, but problems with displacement would appear)
- R_f friction of the footing base R_b and lateral sides R_l against the soil.
- $R_f = R_b + R_l$
- R_c compression resistance of pavement only if it exists.
- R_s by the shear strength by the slab of pavement, if any.

$$Fx \leq R_x = R_e + R_f + R_c$$



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3.3 Vertical pushing force

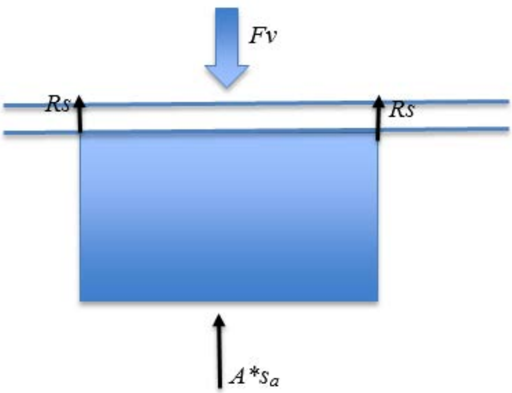
This type of foundation is the one that most resembles the foundations of traditional constructions. In these cases, the vertical load is much more important than the horizontal one or the moment. The analysis of the foundation is practically reduced to find a contact surface that produces a stress on the ground smaller than the soil bearing capacity.

$N / A \leq s_a$

where

N = vertical load
A = footing horizontal surface
s_a= soil bearing capacity

Note that in this case, unlike the case with a pulling force, we do not contemplate at all the friction of lateral sides of the footing. That's because the foundation will not easily move down independently. When we pull up, footing can move up, but when we push down the foundation does not move independently of the adjacent soil (settlement is not considered a movement that causes friction). In any case, if we continued to push the soil, it would break, locally or in a generalized manner, and we would surpass the value of the breaking load or stress. Generally, the value of the soil bearing capacity is obtained by applying a safety factor of 3 or 4 to the breaking stress.



3.4 Inclined pushing force

Inclined compression force is a very common case in tensile constructions. In fact, it is usually more common than vertical compression. Inclined masts are used, above all, to increase the lever arm of the moment that form the vertical reactions at the base of the masts and the stay cables, in most of the perimeter supports (bipods or tripods) .

If we decompose the inclined force F_t in its vertical components F_v and horizontal F_h we can see that the problem is similar to the one we have studied in chapter: Inclined Pulling Load. In any way the vertical compression force has to meet the requirement of

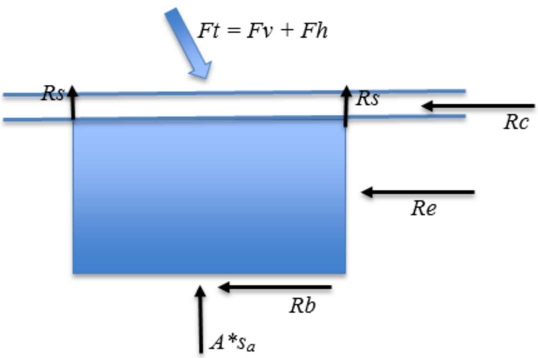
$$F_v / A \leq s_a$$

where

F_v = vertical load
A = footing horizontal surface
s_a= soil bearing capacity

with all the considerations that we have taken into account in the previous section “vertical pushing force”. Moreover we must remember:

- R_e soil lateral resistance. produced by lateral earth pressure E_0 (passive earth pressure E_p could be used, but problems with displacement would appear)
- R_b and R_s could not exist



3.5 Embedded mast

In some cases, especially in the perimeter of tensile constructions we find solutions based on bipods (a mast and a stay cable) or tripods (one or two masts with two or one stay cables respectively) and even more complex sets of masts and stay cables.

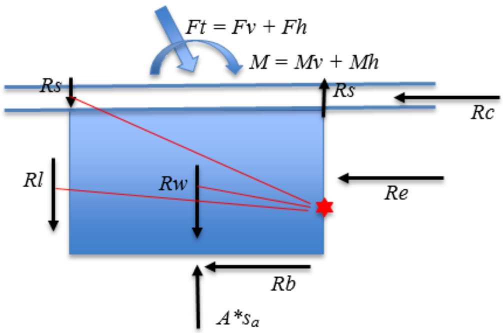
Stay cables usually are usually a hindrance, since they are normally very thin, not easily seen and can cause accidents. They also occupy a space that is not usable, so very often you tend to eliminate them.

To do this, it is necessary to have an element embedded in the base, able to work as a cantilever and support the force that is applied at its top, as seen in the attached image.

The typical triangular shape responds to the distribution of forces in a cantilever. However, sometimes for aesthetic or economical reasons it is preferred to have a vertical element of constant section, as a column or a tube, although it means we use more material than necessary.

In a first approximation it could seem that this is a more economical solution than using a bipod or tripod, but this can be misleading, since one of the great differences between these solutions is precisely the foundation. This foundation will have to be able to transmit the following forces to the ground:

F_h = horizontal force
F_v = vertical force (pulling or pushing force)
M_h = moment due to the horizontal force
M_v = moment due to the vertical force (if the element is not completely vertical)



4. Conclusions.

Designing foundations for tensile structures is a complex task that involves structural and soil technology knowledge as well as very important economical and construction factors. What can be the best solution for a precise case in one location is completely different from what might be chosen in another location. And it should not be considered an error or a mistake.

Equilibrium or balance must be achieved, of course, but to get to this point displacements and other external variables must be taken into account (rain protection, concrete slab pavement existence…). It can be argued that these factors must be taken into account in any type of foundation, but the relative importance is very different when tensile structures are involved. Balancing forces with friction or passive earth pressure implies that significant displacement might exist, and in this case a relaxation of tensile structure stresses might occur as well. Trying to avoid it by ignoring these balancing forces would imply an over-dimensioning of foundations.

References

[1] R. Sastre, *http://www.wintess.com/wintess-manual/foundation/introduction/*, WinTess, 2007