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Seismic effects on a tunnel across the Strait of Gibraltar

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ABSTRACT: It is commonly supposed that tunnels, especially deep tunnels, are safer structures, from the seismic point of view, than surface structures. Although this idea is generally accepted there seems to be some disagreeing opinions about it. It is thought that this Special Theme Session is an opportunity to discuss this subject.

This paper deals with the main concepts in the field of seismic engineering specifically applied to a long railway tunnel bored under the Gibraltar Strait. After a review of a number of cases on earthquake effects on railway tunnels, the case of the Seikan tunnel is considered with more detail because of its similar length and because it is located in a highly earthquake prone region. Finally, the paper shows some conclusions about the way to take into account the seismic effects in the design of a long railway tunnel across the Strait of Gibraltar.

1. INTRODUCTION

In the process of choosing technically and economically viable alternatives for the Europe-Africa fixed link via the Strait of Gibraltar, two solutions remain as finalists. One is a bridge-type solution which, in any of the sub-alternatives considered, will beat all existing records. The other is a bored tunnel-type solution which, if the infrastructure parameters of its Seikan and Chunnel predecessors are adopted (gradients of the access sections of around 12 thousandths, 12 o/oo), will also be longer than the two stated above, and greater also than the deep tunnels planned through the base of the Alps.

Another communication has already treated the problem of earthquakes with regard to the bridge- type solutions for the fixed link. Due to the great differences between the structural typologies of bridges and tunnels, in this communication we are going to talk about earthquakes in relation to the bored tunnel-type solution.

The paper that we are presenting is based on the following conceptual scheme:

- This kind of structure (a large bored tunnel) is not specifically considered in Spanish Seismo-resistant Regulations, as can be deduced simply by reading them and as pointed out in 1982 by one of the authors[1] of these regulations.
- The fact pointed out previously results in the necessity to review carefully the main concepts related to the generation of earthquakes, their propagation and their effects on structures, emphasising those aspects which are specific to a tunnel structure in order to be able to predict or surmise its behaviour, at least in comparison with other types of works subject to regulations.
- The absence of Spanish regulations, and the scarcity of laws in other countries, leads us to research the existing and accessible information on the behaviour of tunnels, especially railway tunnels. Because it is a railway and a very long undersea tunnel (like that of Gibraltar), and moreover it being situated in a country that knows the problem of earthquakes as few countries do, we have studied very closely the documentation relating to the Seikan tunnel, the longest railway tunnel in operation in the world (Japan, 53.8 km). Other japanese railway tunnels have also been studied.

We already anticipate, at least provisionally, the conclusions that we reach in this communication, which are very reassuring in relation to a bored tunnel solution under the Strait of Gibraltar. The provisional aspects arise from the fact that, in the analysis made, we have found a virtually general consensus that underground structures are less affected by earthquakes than surface ones. But we have also found some qualified voices that disagree. One of them, according to the authors of a very recent publication[2], is that of Mr. I. Katayana who, to the best of our knowledge, is the co-author of a communication presented in this World Conference[3].

2. THE MACROCONCEPTS INVOLVED IN THE EARTHQUAKE/STRUCTURES PROBLEM

In spite of the fact that a high percentage of any treatise on theoretical mechanics is devoted to a study of statics, in other words to the equilibrium of material systems, we do not discover anything new if we say that in the real world there is nothing immobile, neither in microscopic nor in macroscopic systems. However, few will doubt the efficiency of the static approximation in the study of many phenomena, particularly in the field of engineering. This includes seismics, as those delegates present at this congress are well aware.

So, when, between the sides of an active fault, a percussive motion takes place in the strictly mechanical sense, in other words, a finite variation in the relative speed of the surfaces in contact in an infinitesimal time interval (a sudden change in the velocity fields of the edges of the fault), this percussion generates a train of complex waves that is propagated in the two semi-spaces defined by the plane (or surface) of the fault. Once this sudden motion ceases (the source of the subsequent earthquake) the two semi-spaces take on a new position of equilibrium or, more properly speaking, of almost imperceptible and, of course, non-percussive motion.

Due to the fact that the ground close to the fault does not allow simple mechanical motion of the edges, the initial (sudden) motion (source of the earthquake) gives rise to a complex stress state (compression/expansion + shear stresses) that are transmitted to successive zones of the surrounding land; theoretically as far as one can imagine.

We could indicate that, as Bolt[4] states, the specialist on the San Andreas fault, H.F. Reid, thought that the vibrations associated with an earthquake could be originated both from the sudden starting of motion and in its sudden stopping: "The sudden starting of the motion would produce vibrations just as would its sudden stopping, and vibrations are set up by the friction of the moving rock just as the vibrations of a violin string are caused by the friction of the bow". This is in line with the mechanical definition of percussion that we have evoked and which, in the case of earthquakes with null initial and final velocities, involves the existence of two percussions in opposed directions.

The modifications in the transmission velocities of the various waves produced by an earthquake, and even the transformation itself of the waves into those of another kind[5], according to the various lithologies crossed and, in particular, the discontinuities found in their path (faults, contacts, phreatics, etc.) mean that the perturbation started in the hypocentre is transmitted, attenuated and modified, to any particle of these semi-spaces.

We prefer to say particle and not point. The motion of a point is defined by a single vector (displacement vector or velocity and acceleration vectors). But that of a particle requires two vectors, for example the velocity of its centre of gravity and the rotation of the particle. Seismographers normally measure the acceleration of a point (or its components in three dimensions which, added vectorially, give us the acceleration vector).

It would be more useful to know this vector, and also the rotation of a particle that contains the point. And, much better, the stresses (or deformations) associated with the six orthogonal faces of an orthohedron surrounding the particle. With this the stress (or deformation) tensor could be known, which is the ideal information from the engineering point of view. Although the technology for obtaining this information exists, at present the inferences on the resistant and deformational behaviour of a particular structure affected by a seismic motion have to be made starting from the measurement (or deduction) of the accelerations of the ground at points close to the structure - along with certain simplified hypotheses on the behaviour of that structure.

The stress/deformational response to an excitation of seismic origin depends very much on the type of structure and (in particular) on its connection to the ground, via which the waves created by the earthquake arrive, more or less attenuated according to the geological/geotechnic formations that they pass through on their way, and on the distance between the hypocentre of the earthquake and the structure.

The Boletín Oficial del Estado [Official State Gazette][6] of Spain states that great bells ring when the seismic intensity felt in the base of a bell tower reaches a level greater than VI on the international macroseismic scale (M.K.S.). There are bells with diameters greater than a metre, which means that the relative motion between the clapper and the bell could be greater than half a metre. The link between the clapper and the bell (ball and socket), which allows motion in any direction, and between the bell and the bell tower, which allows a rotary motion around a horizontal axis, are not models of coupling if it is wished to avoid movement of the bell/clapper unit. The same thing does not occur with the bell tower/ground connection, which is done by means of a rigid link, with the obvious intention of preventing any relative movement. As a consequence of this group of clapper / bell / bell tower / ground links, a movement in the foundations of just a few millimetres, corresponding to an earthquake of intensity VII, leads to a movement of more than half a metre between the bell and its clapper.

We wish to demonstrate with this example that for a material element (structural or not) to move when it is directly or indirectly excited by an earthquake, the links in the kinematic chain that connects the element to the ground have to allow this movement to occur. Or, more precisely: the resultant movement is a function of these links.

Summarizing, we could say that the resultant movements of a particular material element, as a consequence of a particular earthquake, depends on the characteristics of the earthquake (of which, its magnitude is a roughly suitable representation). It also depends on the distance between those material elements and the earthquake, on the geology and geotechnics of the ground separating them and, in a very important way, on the type of connection of the element with the ground.

We are now going to comment on the problem of earthquakes, and tunnels bored into the ground at a certain depth.

3. THE VULNERABILITY OF A DEEP TUNNEL REGARDING SEISMIC EFFECTS

Of the three main factors analyzed (source of the earthquake, transmission of the perturbation created, effect on a particular structure), the planner can act only on the last two (if the function of the structure allows him to do so or requires this).

In the case of a bored tunnel with a thick concrete lining, we have the antithetical case to the example of a bell tower and its bells which are linked to the ground via the foundations. In the case of the tunnel, the structural cylinder is intimately linked to the ground throughout its length, and in such a way that virtually any movement in relation to the ground is prevented if the ground has sufficient rigidity. This explains the hypothesis of the calculation which is very often made when it is wished to estimate the deformations (and therefore the stresses) induced in a tunnel by an earthquake: it is assumed that the structural cylinder takes on the same movement as the surrounding ground. These movements are usually smaller than those that occur in zones close to the surface for the following reasons:

- the stress/deformation characteristics of the ground usually improve with depth, since it is less affected by the various meteorization processes,
- the waves affecting the ground deep down are usually less complex and have a smaller amplitude than those associated with surface areas, in which the large ground/air discontinuity creates reflections that can considerably amplify the effects of incident waves.

The above statement is not of a quantitative nature. Quantitative estimations of the deformations and stresses produced in underground facilities can be found in the technical literature. In relation to these calculations, authors usually say that the deformations obtained as a result of earthquakes are normally very low. Let us look at some examples:

- KUESEL[7], in relation to the design of the BART tunnels (San Francisco Trans-Bay Tube) said in 1969:
  "Except for a few special conditions in weak soil areas, it was found that no additional provisions were required in subway structures for resistance to seismic effects, beyond those required for static load consideration."

We think it is worth mentioning the fact that, in the 1989 Loma Prieta earthquake, several bridges and viaducts suffered major damage, the most important of all of them, the Bay Bridge, used by 243,000 passengers daily[8], was put out of service. On the other hand, the BART Tube suffered no damage and could absorb about 50% of this traffic, going from 102,000 passengers/day before the earthquake to 226,000 after it.

- HENDRON[9] et al., in relation to the design of large underground chambers in seismic areas, stated the following in 1983:
  "In general, in most underground caverns with maximum sizes not larger than 30 to 40 m and built in good to excellent rock materials (shear wave velocities equal to, or larger than, 1500 m/s), the dynamic stress amplifications are almost negligible; therefore, the dynamic stress can be computed as a pseudo-static case."

Opinions and statements on the favourable behaviour of tunnels under actions of seismic origin, not backed up by numerical results (or which do not appear in the documents consulted) are very frequent. Let us look at some cases:

- LEE[10] et al. state the advantages of an underground location for nuclear power plants. In the case of zones with seismic risk there is an undoubted reduction in the design demands for this kind of location.
- The coordinator of a work group of the International Tunnel Association (I.T.A.) on "Seismic Effects on Underground Structures", Mr.HAKALA, said in 1984[11]:
  "For decades it has been observed that subsurface structures suffer very little from ground motions generated by earthquakes. Thus there had been little concern for incorporating seismic design principles into underground facilities."

The author, who is a member of the National Science Foundation, adds that the growing use of the subsoil has given rise to a great variety of forms and sizes for underground constructions, located in very varied geological conditions. Because of this, it is no longer clear that seismic effects are negligible in certain morphological and geological configurations.

In a work for the National Waste Terminal Storage Program of the USA[12], one of whose chapters was devoted to the gathering of data on damage to underground works caused by earthquakes, the following conclusions (among others) were reached:

a) There is very little data on these damages due to the fact that few damages have been caused to underground works. Because there exist mines in areas in which powerful earthquakes cause major damage in surface zones.
b) Wells are also highly resistant to earthquakes. In one of magnitude $M = 8.5$ that occurred in Alaska in 1964, few wells were damaged.

One of the most characteristic works in this regard is certainly the thesis by ROZEN[13], and consequent works based on this that have been published by that author and his supervisor, C.H. DOWDING, on various occasions[14].

This last reference states, on the basis of a graph correlating damage suffered by 71 tunnels studied documentarily with the maximum values of the acceleration of the ground calculated on the basis of certain attenuation laws, that when this acceleration is less than 0.19 g (equivalent to Modified-Mercalli VI-VIII), we are in a "No Damage Zone"; and that when the acceleration is between 0.19 g and 0.50 g (equivalent to MM VIII-IX), we are in a "Minor

Damage Zone". The authors stress that for those last intensities "heavy damage" is expected to above-ground structures. The authors also call attention to the use of the terminology, since particular physical damage to the tunnel (for example, a fragment becoming detached from the facing and falling) may not be important in a hydraulic tunnel, but could, on the other hand, be the source of a derailment in a railway tunnel.

The abstract written as the heading to the thesis states that, although tunnels, in general, experience only minor structural damage, if tunnels experience acceleration greater than 0.85g, then they must be inspected in order to prevent possible accidents caused by small detachments. We think that this is an overly optimistic assessment - at least in the case of railway tunnels. In effect, Japanese railways (in conventional and high-speed lines) have an alarm system that disconnects the energy supply to the trains and immediately starts to operate their brakes whenever the accelerations, measured by seismographs located along the track (coincident with the transformation substation for the haulage energy), exceeds 20 gal (normal lines) or 40 gal (high-speed lines). Remembering that 1 gal = 1 cm/s^2, the alarm is set off (for high-speed lines) when the measured acceleration is 0.08 g. If the maximum acceleration subsequently recorded is between 80 and 120 gal (0.08-0.12 g), then the service is not restarted until the track has been inspected by specialized personnel from a low speed train. And if this maximum is greater than 120 gal (0.12 g) the inspection is made on foot. In any case, these figures seem to be very much lower than the 0.85 g mentioned in ROZEN's thesis.

In any case, the good general behaviour of tunnels against seismic action is recognized by the authors of the international macroseismic scale (M.K.S.) in a somewhat subliminal way but, precisely because of this, surely reflecting a deep conviction. When describing degree XII of the scale (2.4g?) they state: "Virtually all structures are destroyed or left seriously damaged, **even** underground structures". We think that this "even" is the most explicit expression of recognition by experts of the fact that the least vulnerable structures to seismic effects are underground.

Regarding the damage caused to railway tunnels in particular, there is some relatively recent information from Japanese railways[15]. This deals with research into 124 tunnels that suffered some damage as a consequence of 5 old earthquakes of magnitudes between 7.0 and 7.9 (Kanto, 1923). We will point out some aspects of this study:

1. The majority of the tunnels affected had overburdens less than 30 m (80 out of the 124).
2. The most affected zone of the tunnels is the mouth.
3. Damage in tunnels occurred in zones already damaged prior to the earthquake.
4. The damage produced in the 124 tunnels required:

   a) In 71 tunnels, no special measures for restarting the service.

   b) In 24 tunnels, the service was restarted after minor works such as removing soil, protection, etc.

   c) In 29, reconstruction measures were necessary.
5. Only at 11 (eleven) tunnels out of 124, the lining material was concrete. The remaining 113 tunnels had linings of poor materials such as brick and masonry.
6. It is found that running after an earthquake was possible without countermeasures when the estimated maximum acceleration is less than about 250 gal (0.25 g) on the basis of past disasters. This result is in line with that of ROZEN/DOWING, 0.19g, but it is more optimistic.
7. Only 2 of 26 tunnels that suffered heavy damage (required temporary measures or reconstruction) were at epicentral distance longer than 30 Km on the stronger earthquake considered (Kanto earthquake, Japan, 1923).
8. General conclusions of the YOSHKAWA paper were:
   a) In order to prevent earthquake damages, tunnel entrance must be constructed in stable geographical features and in stable geology.
   b) Generally, tunnel design matters little, except the section near the entrance and sections where overburden is thin.

4. THE EXPERIENCE OF THE SEIKAN TUNNEL

Given the great similarity of length and function between the SEIKAN tunnel built and operating in Japan, a country with the most anti-earthquake experience, and the possible railway tunnel in Gibraltar, we have exhaustively searched among the existing literature on the SEIKAN tunnel for what have been the (technical) **obsessions** of the planners, designers and constructors of this enormous, more than 54 km long, tunnel.

To our surprise we found that earthquakes are not one of these **obsessions**. From among some 40 documents that we examined with great care (some of them of European origin but the majority Japanese), we only found a few lines about earthquakes which, added together, would not make up a single page of the size used in this paper. Though the truth is that, for our purposes, they could not be more expressive. We are going to quote some of the few references found.

a) Responding to some questions from European technicians, the site manager, Y. MOCHIDA, stated[16] that from the records of an earthquake that occurred in 1969 (one of the sloping research galleries was being built then) it could be deduced that the amplitude in the tunnel was only 20% of the amplitude on the surface. This, along with the fact that big earthquakes are not very likely to occur in the zone of the tunnel, leads Mr. MOCHIDA to thinking that the effects of these in the tunnel will be **extremely** minor.

b) In a work published in Bautechnik[17], reference is made to an earthquake that took place in the area of the tunnel in 1983, of magnitude 7.7

(Richter), and which did not cause any damage to it, in spite of the tunnel still being under construction.

c) In a special issue of the journal JRE (devoted in part to the Seikan tunnel), 10 research themes on this tunnel are mentioned. One of them (one of so many, we would say in Spanish) deals with earthquakes and the influence on the tunnel, and recommends a preventative system based on the measurements of abnormal deformations in the lining and on abnormal growth of seepage water in the tunnel.

So, the good behaviour of the tunnel (it has lining with thicknesses similar to those of the rest of the network) is noted regarding the earthquakes that have already occurred, as is noted the modest (and reasonable) strategy adopted (far from any unnecessary alarmist attitudes) for registering possible influences of earthquakes.

5. EARTHQUAKES AND THE TUNNEL ACROSS THE STRAIT OF GIBRALTAR

As a consequence of the information obtained during the last decade about the area of the Strait of Gibraltar and of the analysis hereabove, we wish to stress hereafter, as a summary, the following points:

- There is no active fault in the Strait as someone suggested at some time. The existence of such a fault would, at the least, make the viability of a bored tunnel under the Strait doubtful.
- The area near the Strait is, at present, of low seismicity. The intensities, in accordance with existing Spanish seismo-resistant regulations, oscillate between VI and VII (Algeciras: VI; Ceuta: VI; Cadiz: VI; Malaga: VII).
- Preliminary deformation calculations based on the hypothesis that there is no relative movement between the tunnel and the ground, show that the resulting induced stresses are well within the margin of error of the estimated stresses due to the action of the tunnel/ground contact.
- The expected accelerations at tunnel level would not reach the initial alarm level for the modern Japanese railway lines at surface level (0.08g). This means that they would cause no damage.
- Auscultation of tunnel deformations, necessary because of the geological nature of some soils which are also the least favourable from the seismic point of view, will, at the same time, bring forth valuable, and in our opinion sufficient, information about seismic action.
- Error margins in determining the stresses resulting from soil mechanics are more important than the ones resulting from seismic activity.
- We believe that the requirements of information in relation to seismic effects in the bridge alternatives are much more demanding than in the tunnel alternative.

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