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Performances of a reinforced earth structure supporting a High-Speed Train Line – The outcome of 10 years of study

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ABSTRACT

The High-Speed Railway (HSR) project of South Europe Atlantic (SEA) opened on the Sunday 2/7/2017. It allows to link Bordeaux to Paris in only 2 hours. On this line the commercial speed is 320 km/h and the validated speed is 352 km/h. There are 16 walls supporting the tracks, 2 road ridges and 1 underpass wall all done using the Reinforced Earth® technology. The maximum height of the Reinforced Earth® Wall supporting the tracks is 12m high. This wall was equipped with many sensors to follow the behaviour of the Reinforced Earth® Wall during the passage of the high-speed train. This paper presents the outcome of 10 years of studies with a special focus on the results and the lessons learned from the monitoring carried out on SEA.

Keywords: High Speed railway, Reinforced Earth, Numerical analysis, monitoring, Performance

1 INTRODUCTION

Widely employed in roadway applications, the use of Reinforced Earth® in railway construction was given a strong boost with the development of the new High-Speed Rail Lines (HSL) in France. The solution was used in retaining structures on the East HSL connection in Vendenheim, in two structures on the Brittany-Pays de Loire HSL and then in a large number of structures along the South Europe Atlantic (SEA) HSL.

These structures are designed to address a wide variety of specific railway requirements: accessibility during operations, maintenance and deformation-control regarding to the crossed or the supported tracks. A major study program was carried out to remove some uncertainties regarding the fatigue of these structures under high-frequency cyclic loading, but also and more generally to the behavior of structures carrying lines circulated at speeds greater than 200km/h.

This paper summarizes the results of 10 years study with a focus on the instrumentation performed on one of the highest section of SEA project. Results obtained during the test phase at several speeds as well as the ones obtained a year after the commercial opening of the line will be presented and discussed.

2 REINFORCED EARTH PRINCIPLE

The Reinforced Earth concept is based on the friction mobilisation between the fill and the reinforcing strip. The insertion of reinforcements inside the technical fill mass is making the overall a self-stable composite block which can carry very heavy loads.

Fig. 1. Overview of the instrumented Terre Armée wall.

The soil-reinforcement interaction depends on the nature of the reinforcement (geometry, material of which it is made), on the nature and the density of the fill, as well as on the overburden pressure (Schlosser et al. 1981). The definition of the coefficient of interaction μ* is mainly established from pullout test on buried reinforcements in full structures or in laboratory pullout boxes. This coefficient is used for the justification of the adherence criterion in the internal stability verification of mechanically stabilized earth walls. The main international standards (NF P 94270, AASHTO LRFD, BS) require for each layer of reinforcement a verification against a risk of tensile or adherence rupture.

The use of high adherence metallic inextensible reinforcement (Fig.2) is making the reinforced earth technique a solution with a future for the railway development (Freitag et al, 2011).

Fig. 2. HA steel strips.

3 THE OUTCOME OF 10 YEARS OF STUDIES

With the involvement of Terre Armée, SNCF (France's national railway company) and IFSTTAR (French institute of science and technology for transports) initiated a study program in 2007 designed to:

- Quantify the impact of a passing high-speed train on a reinforced soil structure;
- Verify several design assumptions used;
- Validate the use of the Reinforced Earth technique in high-speed railway applications.

This study was developed in three parts:

- A laboratory experiments carried out by SNCF and IFSTTAR on an experimental Reinforced Earth structure under dynamic loading (Soyez, 2009);
- A numerical analysis performed by Terre Armée on a structure under cyclic loading between 2013 and 2014;
- A dynamic instrumentation of a completed structure to provide feedback during the speed ramp-up testing phase and one year later

3.1 Lessons learned from the experimental structure

The full scale experimental wall (Fig. 3 and Fig.4) was realized in Rouen's road experimentation center (CER). The structure is 4.1 meters high and consists of a Reinforced Earth structure on one side and a technical backfill ending in a slope on the other. It represents an 8-meter-wide section of a future HSL. The sleeper is placed 3 meters from the facing, so that it is exactly above the 3.5-meter-long reinforcing strips.

The structure was submitted to two major loading phases. The first phase corresponds to multi-frequency cyclic tests on a big number of cycles and the second phase to tests under heavy static loads. In between these two phases, pullout tests were performed.

The very low residual deformation on the test structure at the end of the fatigue cycles and the subsequent analysis of the extraction tests under dynamic loading showed the absence of fatigue in the soil-reinforcement interface for the high adherence (HA) steel strips.

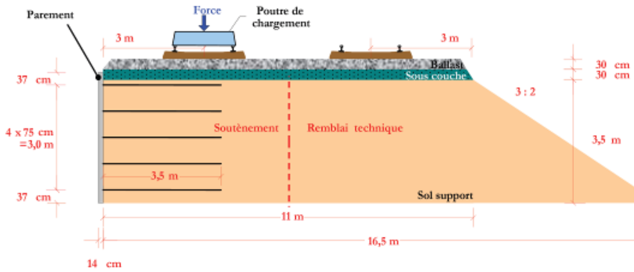

Fig. 3. Longitudinal cross section of CER's full scale experimentation (Soyez et al. 2009).

In addition, for trains passing at more than 250 km/h and thus for the associated high frequency loadings of 25 Hz and more, it was necessary to analyze the phase shift between the compression wave and the shear wave generated by the passage of the train and that propagate through the backfill. Since the stability of a reinforcing strip is a function of instantaneous tensile stress and simultaneous adherence capacity, failure to account of the phase shift could lead to wrong estimation of the structure's safety level. A numerical simulation was therefore necessary to consider this matter.

Fig. 4. View of the experimental Reinforced Earth wall

3.2 The contribution of the numerical modelling (Freitag et al, 2014)

FLAC 2D software was used to model a Reinforced Earth® structure representative of those planned along the SEA by the finite difference method (Fig. 5).

The overall behavior of the structure is obtained by combining its static equilibrium condition with the compression and tensile force increments of a purely elastic model without gravity. This simplified calculation is justified because the structure, based on the extremely low residual wall deformation from the physical testing (less than 0.06mm after the cyclic loading), can be assumed to remain in the elastic domain and therefore subject only to elastic stress increments during the dynamic loading phase. The performance of the monitored structure reinforces this hypothesis. It is also important to clarify that the soil / reinforcement interaction was kept elasto-plastic. A damping factor of 3% was applied in the study.

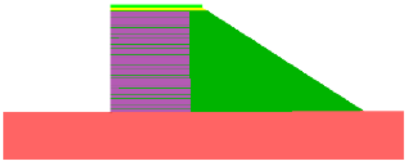

Fig. 5. Model of structure simulated with FLAC 2D

The passage of two standard trains was simulated by the application of “double M” loading curves. The simulated train speeds ranged from 30 km/h to 350 km/h in increments of 10 km/h (Fig.6). For each of these speeds, the study consisted in determining the time at which the tension in the upper reinforcing layer reaches its highest level. Then an instantaneous safety factor against the risk of strip pullout is recalculated. This instantaneous safety factor is the ratio between the instantaneous adherence capacity of the reinforcement and the instantaneous maximum tension. The adherence capacity is obtained by integrating the simultaneous shear stresses between the point of maximum tensile force and the free end of the reinforcing strips. The minimum dynamic safety factor was then compared to the safety factor calculated under static loading. The ratio between the two determines the overdesign factor. An overdesign safety factor of 100% means that the safety level against a risk of strip pullout is equal between a true dynamic and a pseudo-static design approach. When it is less this means that a pseudo-static design approach is unsafe

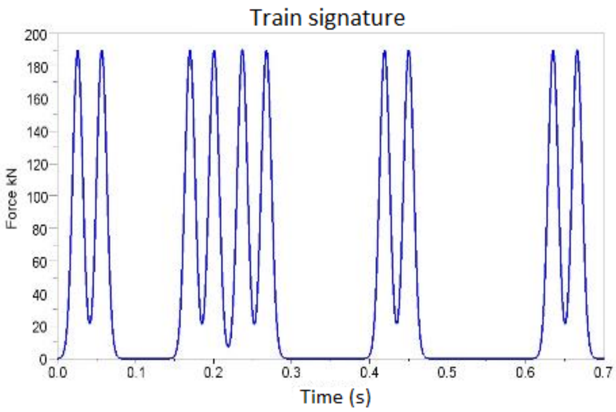

Fig. 6. Loading considered for the train simulation

The simulation came out with the following conclusions:

- The phase shift (Fig. 7) between the time when the maximum loading is applied and the time when the tensile increment reaches its highest level is easily observed. The delay is about 5 ms, which - given the distance between the sleeper and the observation point within the structure - is consistent with the propagation speed of the compression (confinement) and shear (tensile) waves.

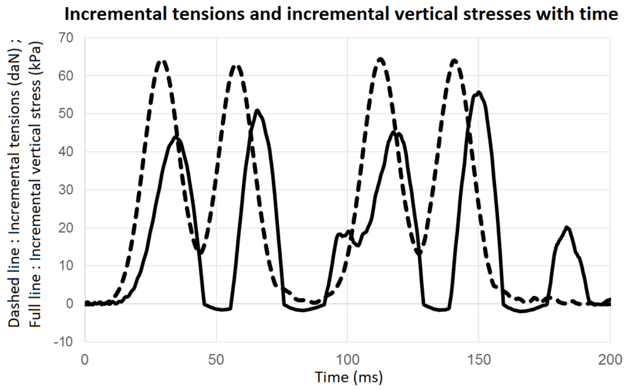

Fig. 7. Phase shift between the incremental vertical stress and the incremental tensions in the reinforcements

- The overdesign factor (Fig.8) against a risk of pullout decreases because of the vibration effects. This coefficient, however, remains high and does not put under question the possibility of a progressive failure of the structure. The overdesign coefficient curves were compared with the standard 1.2 (1/1.2 = 83.3%) factor applied to tensile forces in reinforcing strips as requested in the SNCF guidelines (SNCF. 1985) to take account for vibrations. It was concluded after the analysis that the 1.2 factor would seem appropriate to cover the vibrations generated by the passage of a high-speed train.
- A rapid attenuation of the train vibration induced effect on the overdesign factor against a risk of pullout was demonstrated (Fig. 9). Moreover, beyond 3 meters under the sleeper, the overdesign factor no longer varies between the static condition and the dynamic effects of the train’s passage; there seems to be no dynamic effect below a depth of 3 meters.

4 IN-SITU DYNAMIC INSTRUMENTATION

To obtain feedback before the line is commissioned, the Geotechnical Engineering department of IFSTTAR (a French Public Institute) was asked to develop instrumentation for one of the main SEA HSL structures. This structure was selected on the basis of its greater potential vulnerability as it is the line’s highest (culminating at 12.70 meters) Reinforced Earth structure and will carry trains travelling at a speed of 320 km/h.

The monitoring shown in Fig. 10 is concentrated on the tallest part a grade separator and very close to a concrete crossing structure. The instrumentation concerns 8 panels with their corresponding buried steel reinforcements. The instrumented area covers a zone that is 11m long and 6m high. The instrumented facing panel elements are marked from A to H.

The select fill for this structure is a granular type of fill with less than 8% passing at 80 microns.

The buried instrumentation consists of strain gauges and accelerometers. Three gauges were glued on each instrumented reinforcement at respectively 0.5m, 3.5m and 7m far from the wall facing (see Fig. 11). The accelerometers were placed next to the strain gauge located 7m far from the facing. The accelerometers have a bandwidth of 1,000 Hz and measuring a range of +/- 50g.

A surface instrumentation was also considered by placing accelerometers on the concrete panel surface in addition to topographic measurements. The outcome of this instrumentation will not be presented here because it did not bring anything except that the wall is not moving.

Two measurement phase were carried out. One during the speed ramp-up testing phase and the second one slightly more than one year after the commercial commissioning of the line.

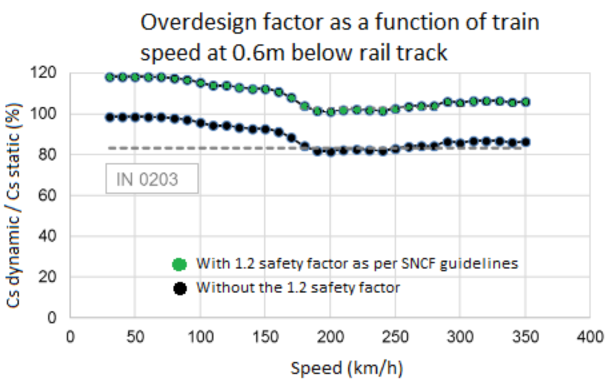

Fig. 8. Overdesign factor as a function of train speed

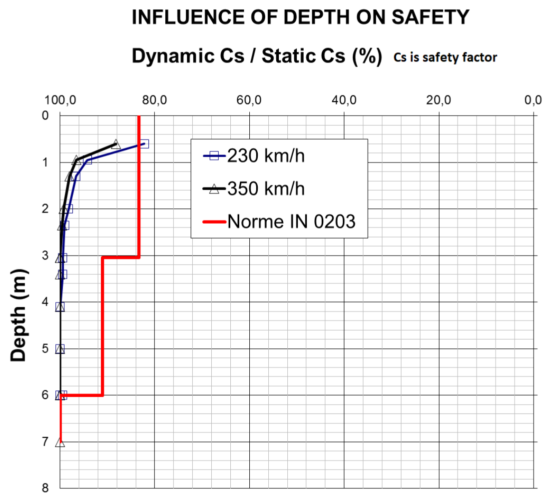

Fig. 9. Evaluation of the overdesign factor with depth

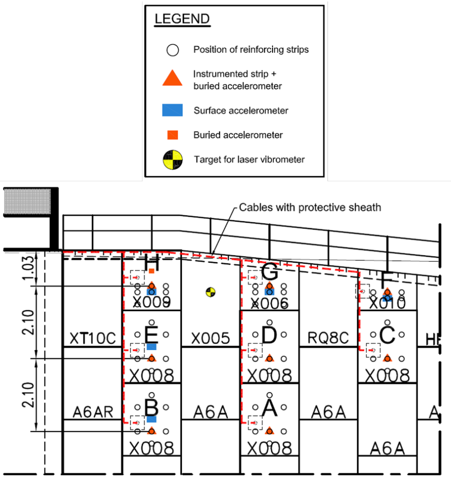

Fig. 10. Location of the instrumented panels

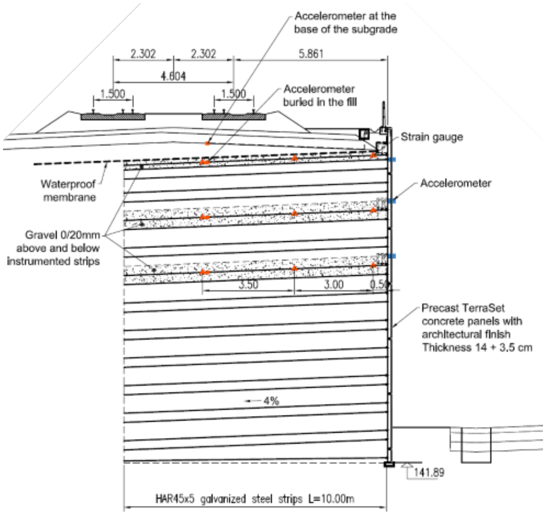

Fig. 11. Location of the instrumented strips with depth

3.2 Outcomes from the ramp-up testing phase

The first measurements were realized during August 2016. During this phase the train speed was ranging from 160 to 352 km/h.

Incremental tensile forces in the reinforcements

The comparison, presented in Table 1, between the maximum measured incremental tensile forces induced by the train passage over the entire test phase and the theoretical ones (including the extra safety imposed by IN-0203-1985) obtained at serviceability limit state, shows that the measured values are significantly lower.

Table 1. Deformation increments due to train load in microstrains.

Depth (m)	Max measured strain (µm/m)	Theoretical SLS values (µm/m)	Ratio measured vs theoretical	IN-0203 extra safety
2.2	20	157	13%	1.2
4.1	10	98	10%	1.1
6.2	5	81	6%	1.0

Fig. 12 is another representation of train maximum induced incremental forces on the reinforcements. The analysis is confirming that the design approach taken by Reinforced Earth in this project is safe and that the real incremental tensile forces are lower than those predicted by the calculation. One of the explanations comes from the fact that the calculation does not consider the distribution by the rail of the train load on several sleepers. Moreover, the train load was modeled as an infinite 50kPa strip load which is conservative.

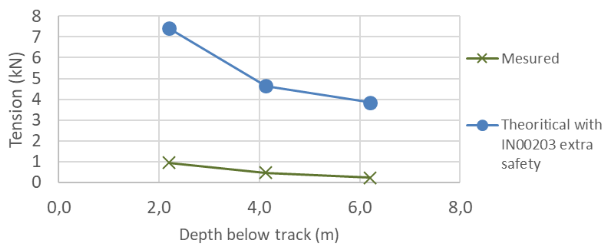

Fig. 12. Tension increments due to the train load

It is reminded at this stage that all the values given corresponds to the maximum increments obtain over the entire measurement phase (all speeds included). Fig. 13 shows the max incremental tensions obtained at the end of the ramp-up testing phase. The very low tension increment values recorded over the entire test and during the last passage of the train allow us to think that the structure does not "feel" the train load at high speed. This conclusion only applies for a running train at high speed and it is not intended to exclude the train loads from the wall design. With a stationary train the conclusion on the incremental loads would have been different.

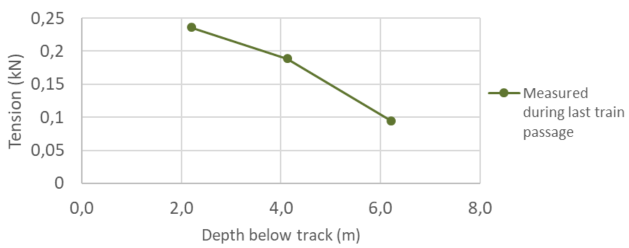

Fig. 13. Tension increments measured during last train passage

Accelerations inside the structure

The raw accelerations data recorded had to be filtered in order to remove some noise generated by some very high frequencies. A low pass filter was applied at a frequency cut-off of 100 Hz. Fig. 14 illustrates the signal after treatment. The consistency of the treatment was demonstrated because the train bogies and axels could be identified.

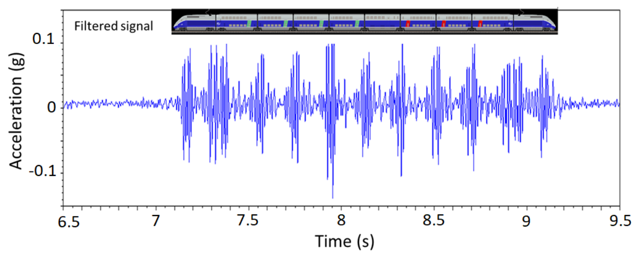

Fig. 14. Example of a filtered acceleration

The analysis of the evolution of the acceleration with depth allows us to see the attenuation of the vibration with depth. Fig. 15 shows a rapid decrease in the maximum vertical acceleration in the embankment as a function of depth. It can be highlighted that beyond 4m the vertical acceleration becomes negligible because the maximum values do not exceed 0.08g.

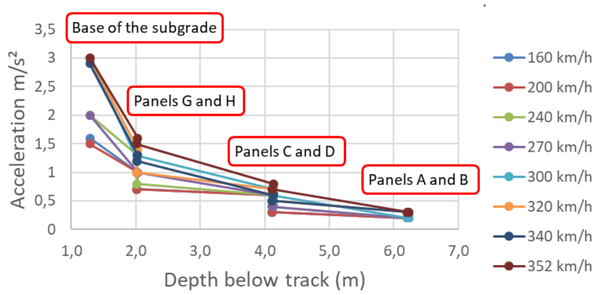

Fig. 15. Evolution of the vertical acceleration with depth

It can also be noted that from the first level of reinforcement located 2m below the rail base, the vertical acceleration does not exceed 0.16g. This level of acceleration is sufficiently low to be able to conclude that an excessive attenuation of the soil overburden pressure on the reinforcement and thus on the soil / reinforcement adherence cannot take place. Moreover, between 0 and 3m this attenuation is fully compensated by the 1.2 additional factor of safety requested by the IN-0203-1985.

3.2 Outcomes after one year operation

November 21st 2017 a second measurement phase took place one year after the commercial commissioning of the rail road. The train during this phase runs at an average speed of 300 km/h. A comparison between 2016 and 2017 measurement will be given in this section.

Fig. 16 illustrates the comparison of the max incremental tension induced in the reinforcements between the last measurement done during the ramp-up test phase and the one in 2017. The difference between both phases is less than 50 Newtons. It can therefore be concluded that after one year the tension increments did not evolve.

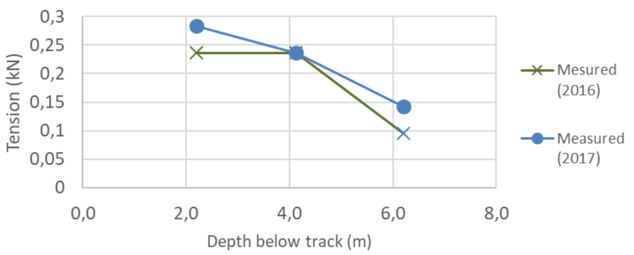

Fig. 16. Tension increments measured in 2016 and in 2017

The evolution of the accelerations with depth was also analyzed in Fig.17. Here again no significant deviation is noticed. Thus is clearly allowing us to foretell that the good stability and performance of the structure.

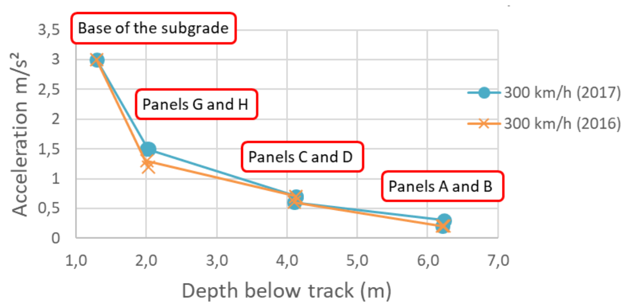

Fig. 17. Evolution of the accelerations with depth in 2016 and 2017

4 CONCLUSION

The experimental block tests confirmed very low residual deformability and the absence of fatigue at the soil-reinforcement interface within the Reinforced Earth® structure under cyclic loading.

Numerical analysis showed a phase shift between the tensile stress variation in the reinforcing strip over time and the variation in vertical strain applied to the resisting part of the reinforcing strips. Although these phase shifts generate a slight instantaneous reduction in the adherence overdesign factor of the strips, this factor remains very high and is well covered by the SNCF guideline's standard safety factors. The reduction therefore causes no concern about a possible progressive failure of the structure. The same results showed that a speed of 320 km/h (or even 350 km/h) would be not more critical than a speed of 200 or 230 km/h. Lastly, the analysis showed that the dynamic effect is rapidly attenuated within the backfill with increasing depth.

This world first instrumentation used on the SEA HSL wall provided feedback from measurements carried out during the speed ramp-up tests and one year after the commercial commissioning of the line. These measurements confirmed the laboratory experiment and numerical analysis results. The structure did not show any evolution which a very good sign that all the expected performances are fulfilled

These various approaches prove that the conventional design method (NF P 94-270 standard), supplemented by the SNCF guideline recommendations (IN-0203-1985) on additional safety for the upper reinforcing layers, result in a fully satisfactory safety level.

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