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3D aspects in a 2.5D BEM/FEM code for soil structure interaction

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ABSTRACT

Some limits of 2.5D models for sol-structure interaction are addressed. First, the problem of micro piles is studied in comparison with 3D FEM full models. In the 2.5D model, micro-piles are replaced by walls of a given thickness which was found to be directly correlated to the 3D pile density. Correspondence between full 3D and approximated 2.5D computations was found satisfactory.

The second problem here reported is the replacement of discrete (3D) damping pads/springs with continuous (2.5D) ones of equivalent stiffness. Here again, this simplification leads to very satisfactory comparisons with full 3D computations. These two problems show that some limitations of 2.5D models can be overcome in a very simple manner.

1. INTRODUCTION

The modelling of ground structure interaction can be addressed with the FEM/BEM approach either in 2D [1], 2.5D [2] or 3D [4,7]. 2.5D models have been showed to be a good compromise between 'quality of results' and 'computation speed'. 3D computations are the most realistic (they can handle any geometry) but lead to high CPUs and limited problem size/frequency range; they are usually carried using 3D-FEM [4] although 3D FEM/BEM calculations are possible [7].

On the other hand, 2D computations are fast but can only model infinite coherent line sources. 2.5D models deal, as 2D, with infinite geometries (along z see **Figure 3**) but can handle point sources and consequently incoherent line sources of finite length closer to real train excitations.

Comparisons between these models have showed [3,7] that for buildings made of slabs and walls, the 2.5D results compare well with 3D models. However, piles, columns, springs for instance cannot be described with 2D approaches. One way to deal with complex buildings is to use hybrid approaches where 3D FEM and 2.5D BEM are respectively employed for building and soil, provided that the underground part of the problem has a 2D geometry [9] (long along z).

Another approach, here presented, is to use 2.5D models to represent some 3D aspects. First, the case of micropiles will be considered and the question addressed will be 'to what extent can we replace a set of micropiles of given density by continuous walls?' Second, the decoupling of the upper floors of a building is often achieved either using springs or damping material applied discontinuously along z. So how can one circumvent the 3D aspect using a 2.5D model?

2. THE MODELS

Two different models have been employed.

First, a 3D FEM model (Nastran software). Each 3D meshing is redone at each frequency and is made of two zones: a constant zone and a varying zone. The varying zone extends beyond the fixed zone with dimensions related to the frequency (the lower the frequency, the longer the extension); it has dedicated absorptive characteristics tuned to avoid unwanted reflections from the mesh endings. This model serves as a reference.

Second, a 2.5D FEM/BEM model [2,3,8] -the commercial software MEFISSTO- developed at CSTB, has been employed. It is a highly optimized code where complex grounds and structures can be modelled.

The 2.5D model is based on 2D geometries (defined in the xy plane and infinitely long and invariant along the z direction, typically train tracks) with 3D sources (a set of vertical uncorrelated point forces to represent a train, for instance). For each frequency a set of sub-problems is defined and solved, each for a given wave number k_z. A Fourier-like integration over k_z leads to the 2.5D solution (therefore going from line k_z excitation to point excitation). The data input for 2D geometries is very simple and consists of contour lines. The meshing is redone at each new frequency in order to optimize computation times. Memory occupation is also optimized. Comparisons between 2.5D and 3D approaches have been published [3,7].

The MEFISSTO software is based on mixed BEM and FEM models where each finite sub-domain can be modelled either with BEM or FEM. As many sub-domains as wanted can be defined, which includes FEM regions. A particular attention is given to points in contact with multiple BEM domains and the presence of multiple tractions, which leads a priori to an insufficient number of equations. It is compensated by the addition of extra nodes where the unknowns are interpolated from the two (or 3 in 3D) neighbouring nodes. This technique was originally proposed in 2D in [10] and applied in 3D [11,4].

It has been showed in [5] that a structure does not have to be very long to be eligible to a 2.5D description and that one may reasonably use a 2.5D model in many situations for structures of, say, a least 10 m of length parallel to train-like sources.

An original feature of MEFISSTO is its ability to compute ground borne noise inside dwellings either by

simple SEA-like radiation (use of a radiation loss factor) or with a precise integral radiation approach mixing 2.5D velocity maps on radiating surfaces and 3D modal Green function in volumes. The combination of 2.75D and 3D has been named 2.75D [3].
It was therefore the author's feeling that the next points that had to be addressed were those concerning 3D aspects such as these here considered.
Figure 1 shows an example of a complex rendering in the case of a building above two tunnels. A vertical force is applied on the rails in the right tunnel. A dual colour map is displayed at 100 Hz: this representation shows both the vertical velocity field in the whole problem but also sound pressure maps in the volumes. **Figure 2** shows a representation of dB(A) values in different volumes (different project).

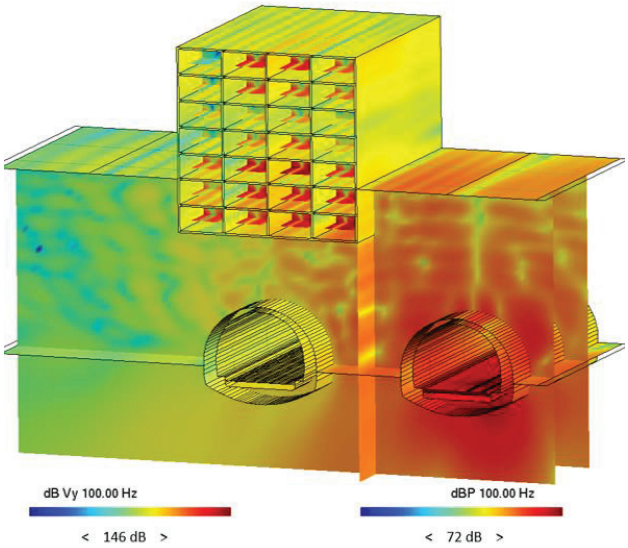

Figure 1 – Velocity level and sound pressure level at 100 Hz

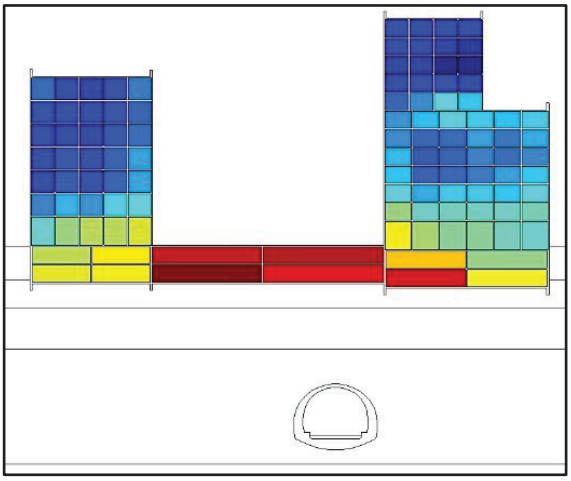

Figure 2 – dB(A) values per volume

3. THE MICROPILE PROBLEM

The foundations of new buildings are more and more often made of micropiles. This construction technique is found to be more economical. It can be characterized by a given density of small piles (diameter typically in the order of 10 to 25 cm). This is clearly not a 2D problem.

The calculations here reported are a first attempt at replacing a set of piles by walls along the z direction (the infinite direction in the 2.5D model) by keeping the contact surface constant. **Figure 3** shows a 3D FEM model of a 6x6 m^2, 20 cm-thick slab resting either on nine 20x20 cm^2 piles or on three walls of the same height (2 m).

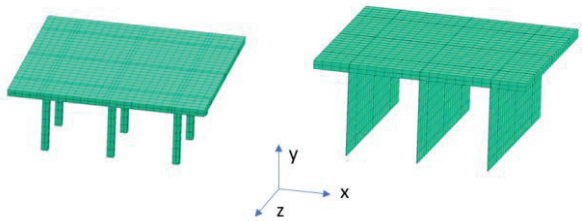

Figure 3. A 9x9 m^2 slab supported by either nine piles or three 2 cm-thick walls (all 2m-high).

The excitation is a force placed either below the piles/walls or on the free surface (**Figure 4**). The ground is made of 2 media. The higher ground has mechanical properties (E=768 MPa, η=0.05, ρ =1800 kg/m^3 and ν=0.33) or (E=268 MPa, η =0.05, ρ =1800 kg/m^3 and ν =0.33) (respectively Young's modulus, loss factor, density and Poisson's ratio). The upper layer has a depth of 2 m, identical to the height of the piles/walls so that the foundation rests on a harder soil. The mechanical properties of the lower soil are (E=2500 MPa, η =0.03, ρ =1800 kg/m^3 and ν =0.41).

The nine piles have a total cross-section of 9x0.20x0.20 =0.36 m^2. Three walls of section 0.02*6 m^2 will have the same total cross-section (wall thickness 2 cm; this thickness being only a computational artifact). We plot the quantity

$$H = LV - Lvref,$$

where LVref is the velocity without piles/walls, the velocity being a rms average over the slab top surface.

Figures 5 and 6 display the results respectively for the buried and surface excitations. Positive values correspond to an amplification with piles/ no piles. The left and right graphs correspond respectively to the softer and harder top layer cases. In each graph, we display the results for the 3D FEM model of 20x20 cm^2 piles and the for 2 cm x 6 m walls (Lz= 6 m) and also the 2.5D BEM/FEM result of the 2 cm infinite walls (Lz=∞).

The 3D FEM computations are made with Nastran. The mesh is made of two regions: a finite portion and a surrounding mesh of varying size (proportional to wavelengths) and adapted damping of high amplitude. The mesh is automatically recomputed at each frequency.

First, for the buried force (Fig; 5), the presence of piles results in a modification of the slab velocity ranging between -4 and + 4 dB (black plots). Replacing the piles by 2 cm walls (red plots) compares rather well with the pile case.

Also, the 2.5D result in green (Lz=∞ instead of Lz=6 m) compares well with the finite 3D FEM results. We can also notice that the type of upper soil layer influences the results; for the softer top layer, the velocity amplification occurs at lower frequencies and that at higher frequencies the piles lead to a decrease of the slab velocity. This behavior is recovered by the 3 computations.

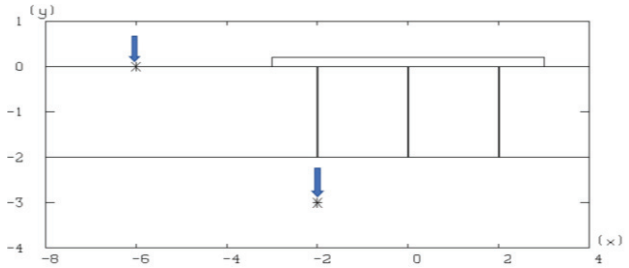

Figure 4. 2D Geometry – Two force positions (*)

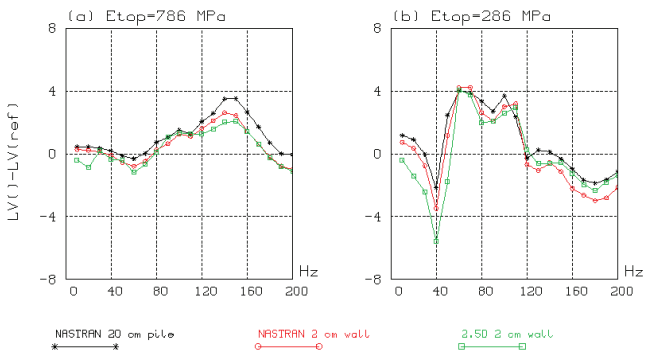

Figure 5. Buried excitation – Effect of piles/walls on average slab velocity

For the surface excitation (Fig.6), the influence of the piles is, as could be expected, less important.

Note the 2.5 D discrepancy between 3D and 2.5D results for the softer topsoil above 160 Hz. This has been found to be due to non-convergence of the 3D FEM results, since 3D FEM computations have been found harder to converge than 2.5D computations and a more refined mesh was found to be too expensive (present results takes 1 h per frequency with the 3D FEM approach).

However, we feel that replacing 3D piles by walls (keeping the same horizontal cross-section) gives the correct order of results. Also, (as demonstrated in [3]) it is possible to replace a 3D structure by a 2.5D geometry

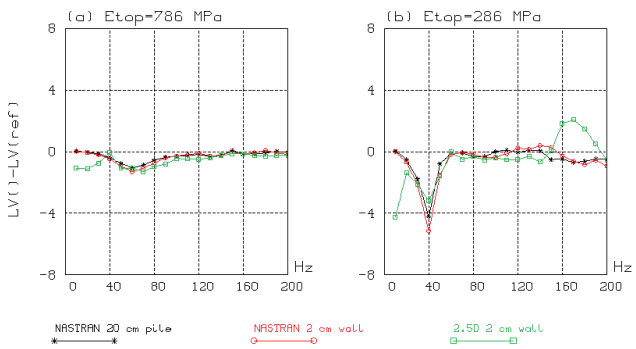

Figure 6. Surface excitation – Effect of piles/walls on average slab velocity

4. 3D DECOUPLING

The problem here considered is somewhat similar to the previous one and concerns the use of non-continuous decoupling solutions (springs or resilient material, both called spring thereafter) applied on 3D structures. The question is 'to what extent can we replace the discrete decoupling by a continuous one along the infinite direction of a 2.5D model?'

4.1 2D situation

We first consider a 2D problem. The stiffness K of a spring-like material with a cut-off frequency f_0 can be estimated from the knowledge of the mass M placed above the spring (one d.o.f. approximation).

$$\omega_0^2 = (K/M) \quad \text{with } K = EW/h$$
$$E = \omega_0^2.hM/W, \quad \omega_0 = 2\pi f_0$$

where E, W and h are the Young's modulus, the total width and the height of the material.

Figure 7a shows the simple 2D geometry first considered. A vertical force is applied on the free surface, 3 m on the left of the structures. Three computation of the average velocity on the top surface are reported: no spring, continuous spring (Lx=6 m), 3 discontinuous springs (Lx=3x20cm=60 cm). The soil is a simple semi-infinite medium with properties (E=25000 MN/m^2, η=0.1, ρ=2000 kg/m^3 and ν =0.25).

The cut-off frequency is chosen as 5 Hz. The values of E obtained for both cases (6 m and 60 cm) are respectively 0.1317 and 1.317 MN/m^2.

Figure 8 (a & b) plots the average velocity level on the top surface (without or with continuous/ discontinuous treatment); either for the geometry of **Figure 7a** (full mass) or for the case where the super structure contains a volume (**Figure 7b**). In all cases the stiffness of the spring is tuned to f_0=5Hz.

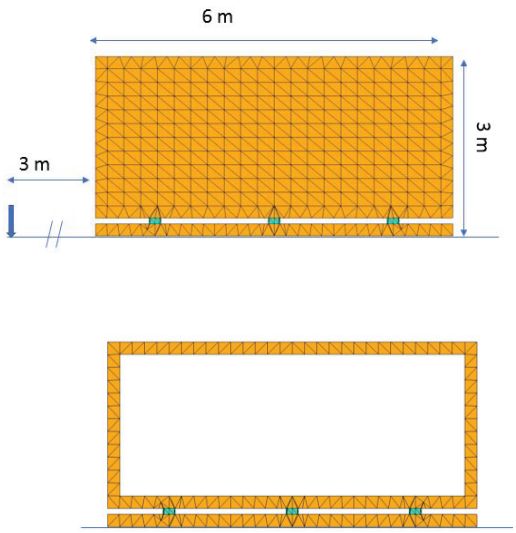

Figure 7. a) Simple mass or b) volume with discontinuous springs (3 x 20 cm)

Above 10 Hz, the springs start being efficient. For the full mass (top graph) the value of H keeps decreasing above 10 Hz except around 180 Hz corresponding to the presence of structural modes.

The results obtained for the more realistic structure of **Figure 7b** (**Figure 8b**) are more complex due to a richer modal behavior. The most important conclusion is that it is legitimate to replace a continuous spring by a set of 3 discrete ones with a properly tuned stiffness, or reciprocally one can replace a discrete spring (along x) by a continuous one.

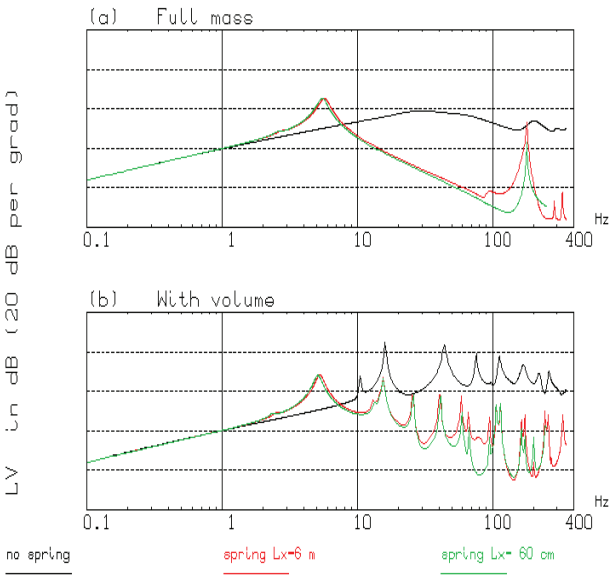

Figure 8. Average velocity level of top surface: no spring, continuous 6 m spring, 3 discontinuous 20 cm long springs

4.2 3D situation

Figure 9 shows a duct-like 3D structure meshed by FEM and the corresponding 2D representation.

The slab is heavily damped (soil damping) but the soil is not modelled (as in [3]). This allows fast 3D FEM computations with no convergence problem as encountered in the previous pile/wall analysis. A vertical force is applied as showed in **Figure 9b. Figure 9b** also shows springs inserted at the top of the ground floor walls.

Figure 9c corresponds to a 3D FEM model with discontinuous springs, whereas **Figure 9b** shows a 2D mesh with an infinite spring along z.

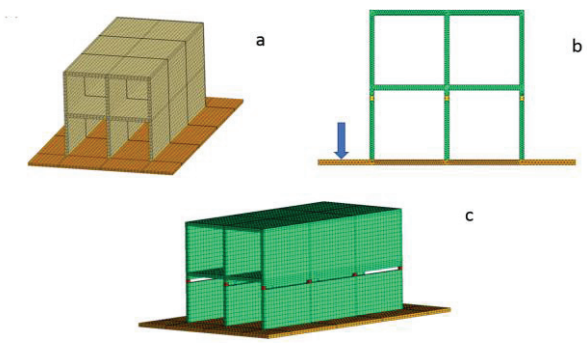

Figure 9. a) 12 m building, b) 2D view with excitation, c) 12 m long building with springs.

First, we consider the case of a continuous spring and see how well the 3D and 2.5D solutions compare, for different lengths Lz of the building (12 m, 28 m and 44 m).

Figure 10 compares, for the right lower floor and right roof, the quantity

$$H = LV(\text{with})-LV(\text{without treatment})$$

The 3D case with Lz=44 m compares very well with the infinite solution. Using a 2.5D model is therefore confirmed to approach very well 3D finite structures [3].

Finally, we come to the core of the subject: replacing discrete 3D springs by continuous ones. To that effect, **Figure 11** compares, at two locations, the spring insertion loss obtained with continuous or discontinuous springs in the case of 28 and 44 m long buildings. Comparing full and dashed lines shows a correct agreement between continuous and discrete springs. On the top slab, above 40 Hz, the attenuation exceeds 20 dB.

Above 80 Hz, the continuous calculation gives a higher level thus underestimating the spring efficiency (solid vs dashed lines), but this occurs when the velocity level has already decreased by more than 20 dB. So, globally, one sees that it is possible to replace a 3D discrete placement

of springs by continuous one thus allowing 2.5D calculations.

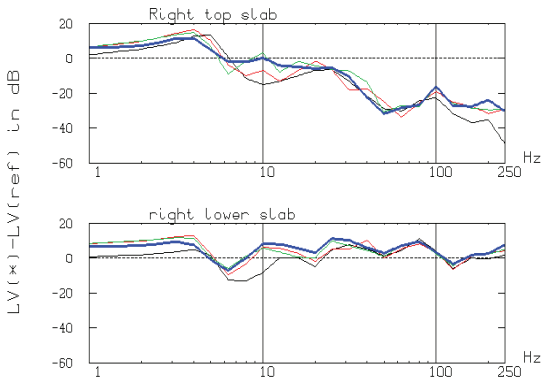

Figure 10. Continuous spring: comparison of H(3D) (different building lengths Lz=12 m, 28 m 44 m) and H(2.5D): Lz infinite. 1/3 octave band.

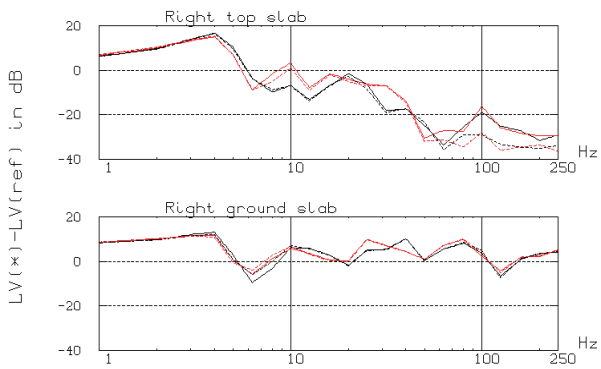

Figure 11. Comparison of continuous (solid lines) and discontinuous springs (dashed lines) along z. **28 m** and **44 m** buildings.

4.3 Static computations

It should be noted, that more precise computations for the values of the required spring stiffness are in practice necessary. The 2.5D BEM/FEM software Mefissto, here employed, can compute the static response at any location and thus permit more precise dimensioning of springs or resilient material.

We show an example of such a computation. The building considered has a non-constant (**Figure 12**) number of levels so that the static load should vary along the horizontal position x.

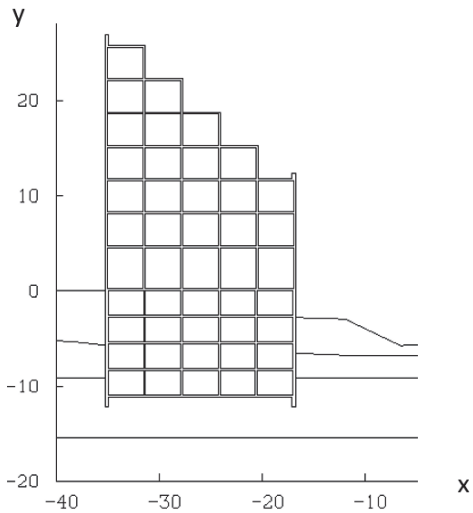

Figure 12. Geometry of the building

Figure 13 shows the variation of the static load in the lower part of the building.

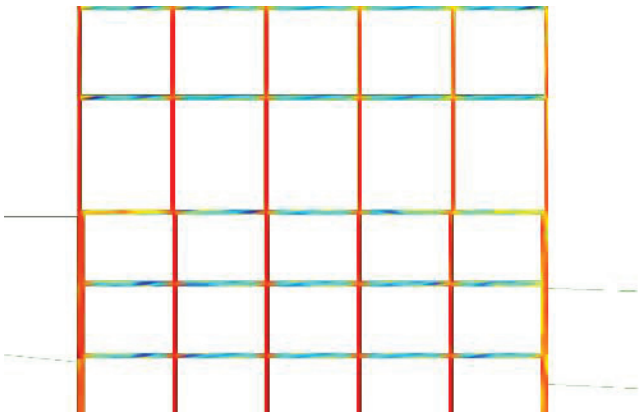

Figure 13. Variation of the static load

We want to insert springs at the top of the ground floor (between y=4.3 and 4.4). We therefore plot a crosscut of the static load at y=4.3 (**Figure 13**) as it varies along the width x (6 plots for the 6 walls).

The outer walls have a thickness of 16 cm and the inner walls are 18 cm thick. The range of variation between walls is about 10 dB. The detailed knowledge of these variations will help in optimizing the choice of the springs of resilient material.

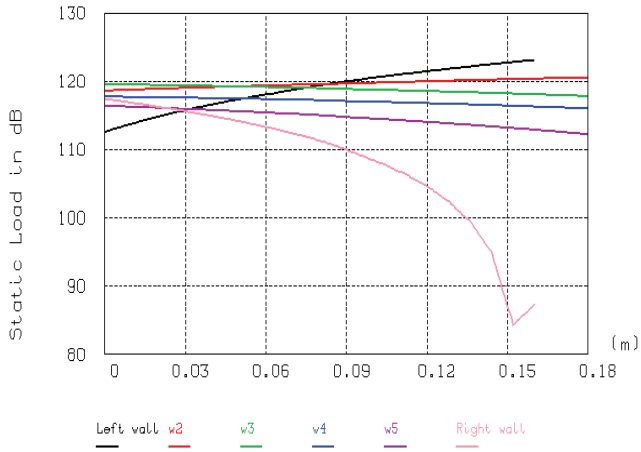

Figure 13. The static load for the 6 walls (y=4.3) as a function of x.

5. CONCLUSION

Using a 2.5D model to tackle 3D situations has been showed [5] to be correct in the case of walls and slabs buildings. In this paper, we consider two 3D situations that can also be modelled in 2.5D.

First, the case of a building resting on micro piles can be approximated by a building on buried walls provided that the total horizontal contact cross-section is preserved.

Second, we also show that discrete springs can be well approximated by continuous ones. Computing the variations of the static load is necessary in complex situations.

The case of a building made of slabs and pillars cannot yet be modelled using a 2.5D approach. Coupling a 2.5D model for the ground with a 3D FEM model [6,9] for the structure is a way to do it. Further developments on this topic are part of ongoing research.

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