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Ground motion simulation by hybrid methods

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ABSTRACT: Complex interactions between source, path and site effects require combined simulations, called hybrid methods. The Volvi sedimentary basin at EURO-SEISTEST near Thessaloniki, Greece, is investigated. The recently developed DW-FD method is applied. The source and path effects are simulated by the Discrete Wavenumber method for a point double-couple source and a 1D crustal model, while the site is treated by the Finite Difference method for a 2D model. To extend the hybrid approach to more realistic crustal structures, a new hybrid method based on the combination of the Ray and FD method is developed. Although the R method may suffer from incompleteness of the wave field, the basin response calculated by DW-FD and R-FD are similar. This encourages further developments of the R-FD method wherever the 2D and 3D crustal propagation effects are significant.

1 INTRODUCTION

Basins, valleys, ridges, featuring a 2D structure, allow detailed Finite Difference (FD) studies at a modest cost, if excited by plane waves. Considering, however, excitations by point double couple sources embedded in realistic crustal models introduces 3D model features. Anyway, useful approximate solutions still can be obtained with 2D FD codes, if combined with 3D excitations through hybrid methods (Faeh et al., 1994, Rovelli et al., 1994).

The objective of this paper is to apply the recently developed DW-FD hybrid method of Zahradník & Moczo (1996) to the Volvi sedimentary basin at EURO-SEISTEST near Thessaloniki, Greece (Jongmans et. al. 1998). In this method, the source and crustal propagation are solved by the Discrete Wavenumber in a 1D structural model. For future extensions to 2D and 3D crustal structures, the ray method is employed, and a new R-FD method is investigated. This is primarily a methodical paper. Comparisons with field records are left for a separate paper; see also Riepl (1997).

2 METHODS AND RESULTS

The method is explained with reference to the example of Figure 1, considering a model earthquake and a profile across the Volvi sedimentary basin. Figure 2 and Table 1 give the Volvi basin 2D cross-section. For the crustal structure, see Table 2. The goal is to simulate ground motion at the studied profile, unifying the source, path and site effects.

The method is basically that of Zahradník & Moczo (1996). The wavefield due to a point source and 1D crustal structure is the so-called background field, or excitation. In the first step, the excitation is calculated and saved for discrete points along

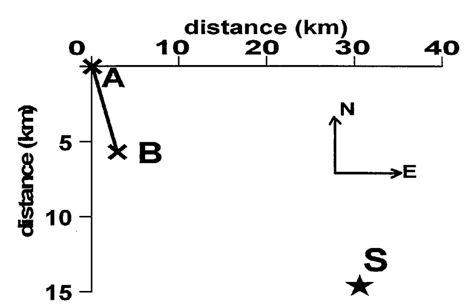

Figure 1. The epicentre of a model earthquake shown by the star (moment=1E+16Nm, corner frequency=3Hz, depth=7km, strike=75DEG, dip=75DEG, rake=-120DEG). The studied profile AB, crossing perpendicularly the Volvi basin, is detailed in Figure 2.

rectangular 'excitation lines', surrounding the whole basin from the left and right sides, as well as from below. The basin itself, however, is absent during this step. The entire medium is represented by the 1D crustal model. In the second step, the source is already absent, but the basin is present inside the excitation box. The background wavefield of the first step is continued inside the excitation box through the basin, and is 'recorded' at the Earth surface. Outside the excitation box the so-called residual field is calculated, that represents a difference between the complete field (the basin effect included) and the background field.

Two methods are used in the first step, the Discrete Wavenumber (DW), and the Ray (R) method. The second step is done by the Finite Difference (FD) method. As for the DW and R methods, see Coutant (1989), and Červený & Pšenčík (1988), respectively. The FD method is basically that of Zahradník (1995), Zahradník & Priolo (1995), and Opršal & Zahradník (in press), with some stabilization modification necessary due to high Vp/Vs ratios and fast spatial variations of this ratio (Opršal and Zahradník, submitted). The FD grid steps are 5.0m and 0.0007s, thus correct results are up to 4.6Hz.

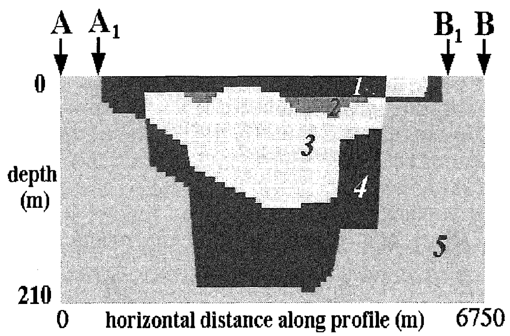

Figure 2. The Volvi basin cross-section along the profile AB of Figure 1. For parameters of the blocks, see Table 1. Arrows A_1, B_1 show the position of the vertical excitation lines, their horizontal distance along profile is 605m and 6145m, respectively.

Table 1. Parameters of the Volvi basin model.

Block No.	Vp (m/s)	Vs (m/s)	ρ (kg/m³)	Qp=Qs
1	460	230	1750	20
2	1500	300	2000	30
3	1800	425	2200	40
4	2600	700	2300	60
5	4000	2300	2500	100

Table 2. Crustal model.

Depth (km)	Vp (m/s)	Vs (m/s)	ρ (kg/m³)	Qp	Qs
0.0	4000	2299	2500	200	100
2.0	5700	3276	2840	200	100
3.0	5750	3305	2850	200	100
4.0	5800	3333	2860	200	100
5.0	5850	3362	2870	200	100
6.0	5900	3391	2880	200	100
7.0	5950	3420	2890	200	100
8.0	6000	3448	2900	200	100
9.0	6050	3477	2910	200	100
10.0	6100	3505	2920	200	100
20.0	6740	3870	3050	300	150
30.0	7310	4200	3164	300	150
40.0	7770	4465	3254	400	200
60.0	7970	4580	3294	400	200
90.0	8100	4680	3320	400	200

The 3D background field is calculated in the E,N,Z geographic co-ordinate system. The 2D FD method works in the local X,Y,Z system (X,Z in the cross-section of Figure 2). Therefore, the excitation is first rotated into X,Y,Z system, and the subsequent FD calculations are separated into the P-SV and SH motions, in the X,Z and Y direction, respectively. Only the P-SV case is studied in this paper.

A specific feature of the model is the source located off the investigated profile AB. This, together with the point double-couple character of the source, introduces significant 3D features, strictly speaking inconsistent with the 2D calculations for the cross section AB. The question whether the 3D-2D inconsistency yields unacceptably high errors, or whether the inconsistency is low enough, requires a special (model dependent) consideration. In the so-called 'replication experiment' we formally apply the hybrid method, but without any basin in the 2nd step (medium inside the excitation box still represented by the same 1D model as in the 1st step), and compare this solution to the direct DW solution. Or, alternatively, we inspect the residual field outside the excitation box. If the hybrid and direct solutions are close to each other (i.e. the residual field is weak) we consider the 3D-2D inconsistency negligibly low, thus indicating that the hybrid method is applicable.

The DW-FD replication test in Figure 3 does indicate acceptably low 3D-2D inconsistencies in the

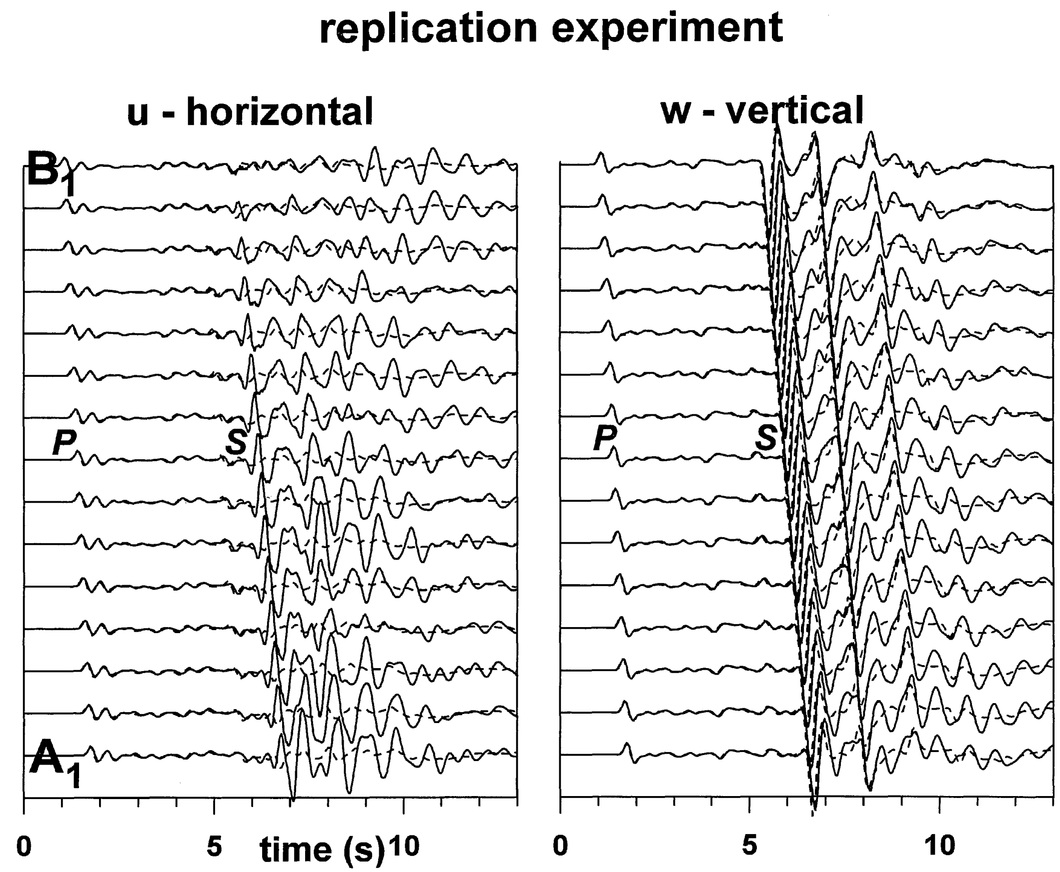

Figure 3. The replication experiment. This is a comparison of the formal DW-FD solution (solid line) with the straight DW solution (dashed line) for a purely 1D crustal model, without any sedimentary basin. The 15 receivers are located on a free surface along the profile with a constant horizontal spacing of 395m, the first and last receivers are placed at A_1, B_1 (See Figure 2), respectively. *S* and *P* denote the phases of the waveform. The geometry showed in Figure 1 causes a visible time delay of the arrivals to receivers along the profile. The figures show a very good agreement in the replication of P-waves and the first part of the S-wave (up to 7s). The inconsistency, however, does affect just a part of the whole synthetics, and there is a good 'replication' of some phases even in times of 9s, (see the vertical component).

studied example (a very good agreement up to 7s). We explain this favorable result as follows:(i) The 3D excitation features are relatively weak because the profile is short, compared to the epicentral distance, and it is seen at a small angle, (ii) The 3D excitation features are relatively well transferred to the FD model because the excitation box is a rectangle surrounding the whole basin. Thus the remaining inconsistencies are only those connected with the approximate 2D propagation of the initially 3D disturbance at a relatively short distance of the FD model.

Table 3. Elementary waves included in the R solutions.

Model	Elementary waves
SIM	P,PP,PS,S,SS,SP *)
COM	as SIM, plus SS2S,SS2SS,SS2SP +)

*) direct waves and surface reflections
+)reflections from the 2 km discontinuity

Before proceeding to the hybrid method, we compare the excitations simulated by the DW and R

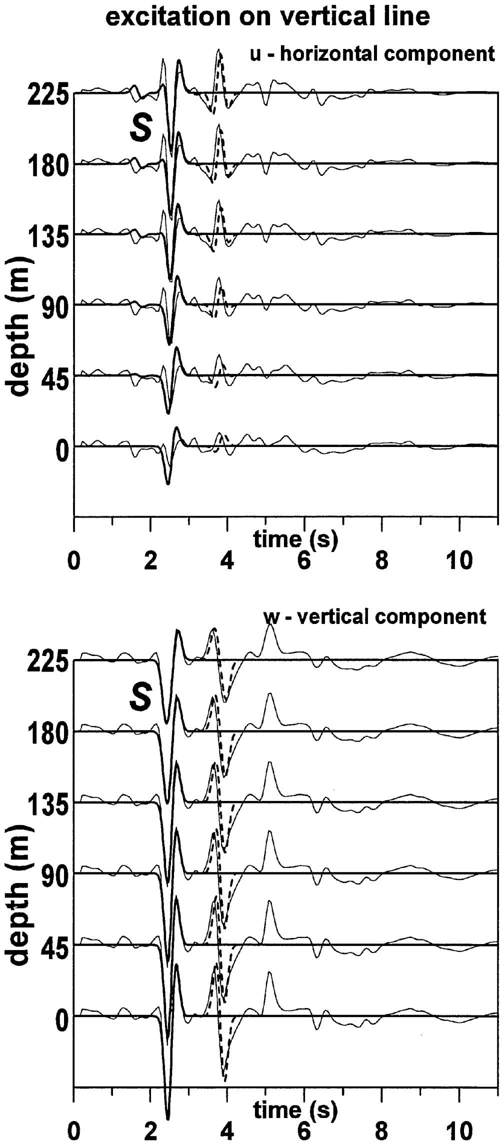

Figure 4. The comparison between the DW (solid thin line) and two R (COM -dashed thick line, and SIM -solid thick line) background solutions for 6 receivers distributed along the vertical excitation line placed under A_1.point of the profile (see Figure 2), depth of the receivers is specified in the graph. By *S* is denoted the start of S and later phases. Note the exact agreement between R-COM and R-SIM up to arrival of phases missing in R-SIM. A relatively good agreement between DW and R solutions is visible. Zero value on the time axis corresponds to 4.2s in Figure 3. For the wave coding, see Table 3.

method (Figure 4). Two ray solutions are tested, including different number of the elementary waves (reflections, refractions, conversions), see Table 3. The first is simplified solution with few rays only (SIM), and the other is more 'complete' solution (COM). It is not easy to guess how many rays should be used in order to make the R solution 'complete enough', i.e. close to the DW solution, in particular in crustal models with several low velocity layers at the top. Thus the wavefield incompleteness is the main risk of the R-FD solution performed without any DW check. On the other hand, a question arises, how the incompleteness of the R solution will affect the basin response evaluation. This question is addressed below.

Finally, let us proceed to the hybrid solutions, DW-FD (Figure 5) and R-FD (Figure 6). Both are produced only for S and later arrivals (zero in time axis of Figures 5 and 6 corresponds to 4.2s of Figure 3). The R-FD is presented in two versions, corresponding to the SIM and COM excitations. The ground motion at the Earth surface profile AB is presented (the receivers located between A_1 and B_1 with equal separation of 395m as described in Figure 3). The main finding is that the R-FD and DW-FD basin response is similar, especially in terms of the relative amplifications and deamplifications along the profile, e.g. the high differences for neighbouring receivers on bedrock and sediments. Other interesting point in Figures 5 and 6 is very different behaviour of the horizontal and the vertical components. The local amplification above the thin low-velocity layer features both, R-FD and DW-FD simulations. The response of the site is typical by presence of low velocity surface waves propagating along the basin. This applies not only to the DW-FD and R(COM), but also to the R(SIM) solution, whose excitations were significantly different, but the site responses are very similar (see comparison in Figure 6).

3 CONCLUSIONS

The DW-FD and R-FD hybrid methods are powerful tools for the unified simulations of the source, path and site effect. The double couple sources introduce 3D excitation features, particularly strong for point sources located off the investigated 2D cross-sections. The so-called replication experiments can be used to evaluate the 3D-2D inconsistency, and decide (before the FD calculation) whether the hybrid method can be applied, or not. Another important task is how many elementary waves must be summed up to provide a reasonable R excitation (never as complete as the DW excitation). For the

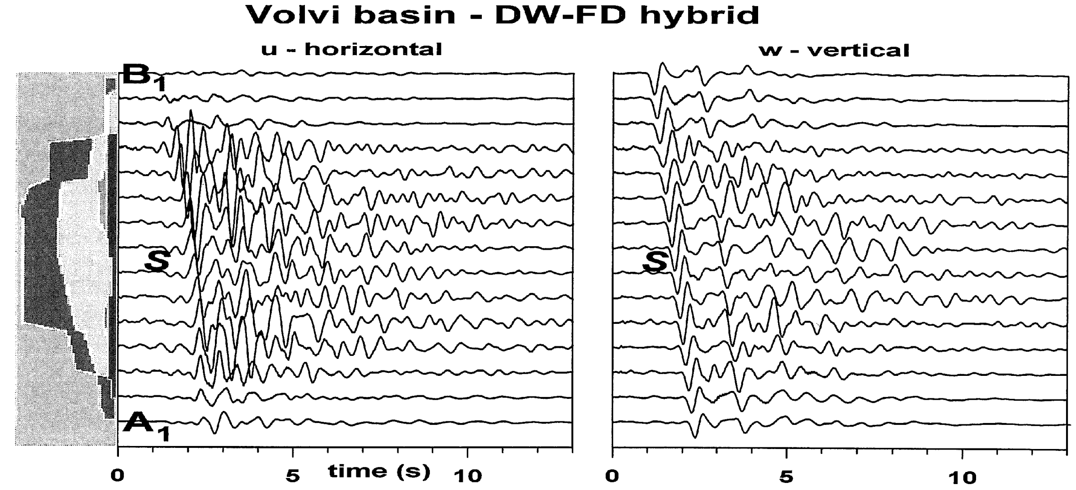

Figure 5. The DW-FD ground motion simulation at Volvi basin. S denotes the arrival of S-wave, the zero of the time axis correspond to 4.2s in Figure 3, A_1 and B_1 correspond to positions on profile as depicted in Figure 2. The receivers are placed on surface between A_1 and B_1 with constant horizontal abscissas of 395m. The figure clearly shows the change of the arrival time delay along the profile. However being of a higher amplitude at the arrival, the vertical component of the ground motion is much weaker then the horizontal one due to the conversion. These DW-FD synthetics also feature of low velocity surface waves trapped in the area of the basin. Some receivers show a high amplitude signal of very narrow spectrum

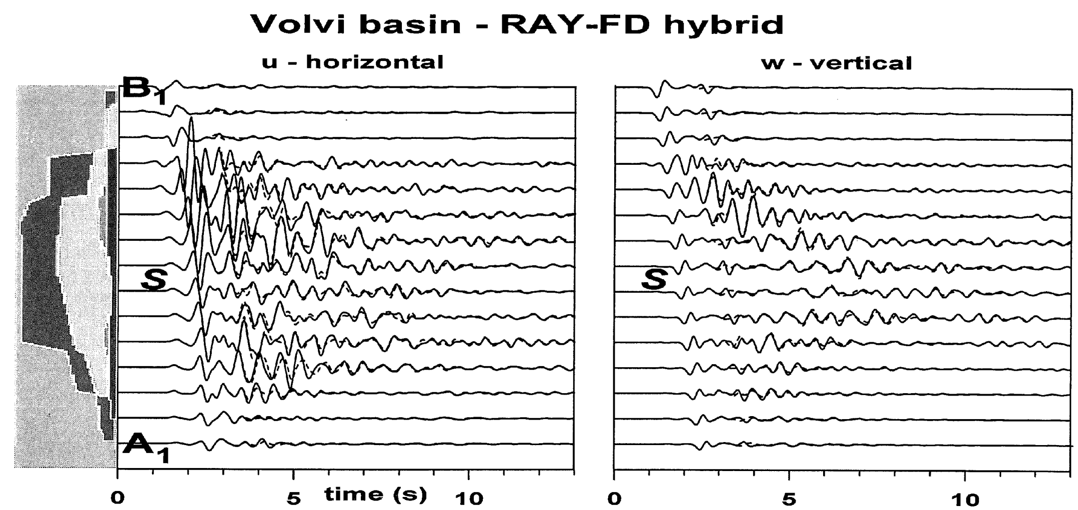

Figure 6. The RW-FD ground motion simulation at Volvi basin. SIM solution by the dashed line, COM by the solid line. The meaning of S, A_1, B_1; the position of the receivers and the time shift of the seismograms are the same as in Figure 5. The comparison of the SIM and COM R-FD hybrid shows a very good agreement. The difference between the excitations is shown in Figure 4. It is significant, that even the SIM excitation is weak and of a simple time history, compared to the consecutive site response. The solutions are rather similar to that shown in Figure 5 with same features as weak first arrival and relatively stronger response in horizontal component. The surface waves propagating along the profile are also well visible.

Volvi sedimentary basin, studied in this paper, both DW-FD and R-FD hybrid methods provided relatively similar basin response, at least sense of the relative sense of the ground motion variation along the surface. Important point is also the very small difference between simple and more 'complicated' R-FD computations. This encourages a further development of the R-FD method, which, opposed to DW-FD, allows 2D or 3D crustal propagation effects to be included.

ACKNOWLEDGEMENTS

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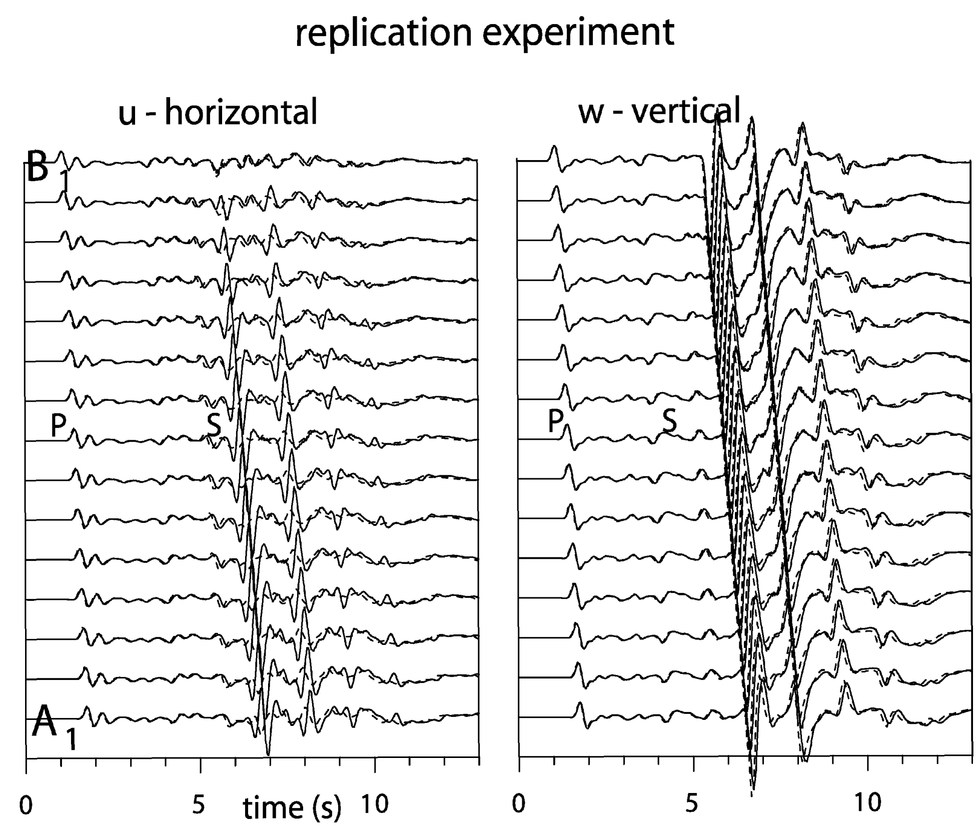
Errata to Figure 3 of
Oprsal, I., Pakzad, M., Plicka, V. & Zahradnik, J., 1998. Ground motion simulation by hybrid methods. In: Irikura, K. et al. (eds.), The Effects of Surface Geology on Seismic Motion , Balkema, Rotterdam, pp. 955-960 (Proceedings of ESG'98, December 1-3, 1998, Yokohama, Japan).



Errata to Figure 3 of Oprsal et al, 1998.
The right hand figure (corrected) is the actual replication test synthetics. The fit at left-hand panel should be the same (since it is second component of the same ground motion) as at the panel on the right-hand side, however, the data for it were not re-covered from 1998 computations archive.

Original text:
Figure 3 The replication experiment. This is a comparison of the formal DW-FD solution (solid line) with the straight DW solution (dashed line) for a purely 1D crustal model, without any sedimentary basin. The 15 receivers are located on a free surface along the profile with a constant horizontal spacing of 395m, the first and last receivers are placed at A1, B1 (See Figure 2), respectively. S and P denote the phases of the waveform. The geometry showed in Figure 1 causes a visible time delay of the arrivals to receivers along the profile. The figures show a very good agreement in the replication of P-waves and the first part of the S-wave (up to 7s). The inconsistency, however, does affect just a part of the whole synthetics, and there is a good 'replication' of some phases even in times of 9s, (see the vertical component).