Seismic Retrofitting of Existing Structures with Insufficient Seismic Safety using Dispersed Vertical Panels in High Seismicity Regions

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Abstract:- **After the introduction in 1979 of the first seismic regulations in the building standards of the Albanian Code (Standard KTP, 1979), the design requirements became even tougher in the later standards in 1989. To gain clarity over the necessity to perform a retrofit, existing buildings should be examined. The goal of seismic retrofitting is the improvement of seismic behavior of structures. This can be achieved by different strategies, such as improving regularity, softening, strengthening, increasing ductility, reducing seismic action through damping, mass reduction or even by changing the use of the building. A reduction of seismic action can be achieved also by combining the above strategies. A seismically suitable retrofit should be optimally coordinated for the combination of three distinctive features of a structure: stiffness, ultimate resistance and deformation capacity. The classical retrofitting strategy is the strengthening of existing structural systems through new building elements or through the doubling of existing building elements as, for example, through new reinforced concrete walls or steel trusses. Retrofitting strategies that are focused solely on one distinctive feature of the structure should be avoided. The application of continuous vertical anti-seismic shear walls represents an effective method for the fulfillment of the above requirements and the reduction of the seismic risk. However, using vertical continuous seismic shear walls provokes unsolved problems and in many cases, it is impossible from architectural and functional point of view. This publication provides a detailed and practical solution to the seismic retrofitting of existing structures, which consists in distributing the shear wall panels in a discontinuous manner. As it is verified and documented through an extensive parametric study of various building cases, employing a discontinuous arrangement of the wall panels across the height of the building is not accompanied by a less satisfying seismic reaction compared to the case of continuous vertical seismic walls. With additional walls it increases considerably the resistance of objects versus horizontal displacements and reduces the deformation. At the same time, many morphological, conceptual weaknesses of these objects are corrected, such as soft stories, eccentricity in plan and short columns.**

Keywords: Seismic safety, discontinuous walls, ductility, stiffness, deformation capacity.

1   INTRODUCTION

In the current construction industry, there are two main methods prevailing when it comes to retrofitting building structures against seismic actions: continuous walls and column jacketing. In this paper, we will discuss the advantages and limitations of an alternative method, which uses discontinuous RC walls or steel braces.

Firstly, a general and simple method of discontinuous RC walls (steel braces) will be looked at, considering the positive impacts that it would have on an existing building. Later, a more academic approach will be introduced, which explains a method of finding the optimal distribution of walls in a building.

1.1   Discontinuous RC Walls/Steel Braces on a Simple 2D Frame

1.1.1   Introducing the Method of Discontinuous RC Walls/Steel Braces

An alternative solution to overcome the practical problems arising from using continuous walls is offered by installation of discontinuous reinforced concrete walls or steel braces. This method corrects many morphological, conceptual weaknesses of existing objects such as soft stories, eccentricity in plan and short columns. This technique, although repeatedly implemented in practice, it has not been the object of many academic researches that would highlight its advantages and disadvantages.

In this paper, accepting the predominance of mixed systems (frame & walls) over the pure frame structures, some basic conclusions from the comparison between continuous and discontinuous RC shear walls (steel braces) will be shown.

Because of the limited space in this publication, a simple 2D frame is adopted to illustrate the comparison exercise between the two methods. For simplicity, RC walls or steel braces will be called panels from now on.

1.1.2   Analysis of the 2D Frame

The technique of discontinuous panels goes against the current practice, according to which the continuity of the vertical elements (columns and panels) is an essential requirement for either new or existing buildings. The main purpose of this requirement is to avoid the creation of a flexible (soft) floor and, as a result, losing the regularity of the horizontal displacements of the floors across the height of the building. In order to test whether this characteristic of continuous panels is affected by the placement of discontinuous a flat mixed frame with a panel in three different variations of its layout is considered as example:

a) Continuous panel
b) Interrupted panel
c) Rearranged panel

It is a reinforced concrete four by four frame with beam cross sections of 25 x 50 cm and columns 50x50 cm. Beams are considered to be infinitely stiff (diaphragmatic function) for the purpose of this exercise. A 20cm wall is placed on span B-C. In the first case considered, the wall is continuous, in the second it is interrupted at level 2, while in the third case the level 2 wall has be transferred from span B-C to span E-F (see Figure 1). The horizontal loads applied on the frame are triangular and are applied as axial, linearly distributed loads on the horizontal beams of the axis 1 to 4 (F1 = 100.0 kN, F2 = 200.0 kN, F3 = 300.0 kN, F4 = 400.0 kN).

Results of the static analysis of these three cases are shown in Figure 1. It is noted that wall simulation is made with surface finite elements. Between the continuous wall and the interrupted wall cases there is an extremely large increase in the horizontal deflections (+ 350%) and in the internal forces for the elements on Level 2. For instance, column A experiences, an increase in moments of + 700% and increase in shear forces of + 700%. This fact was, of course, to be expected, due to the sharp reduction in the rigidity of this level (creation of flexible - soft - floor due to its removal wall on the second floor).
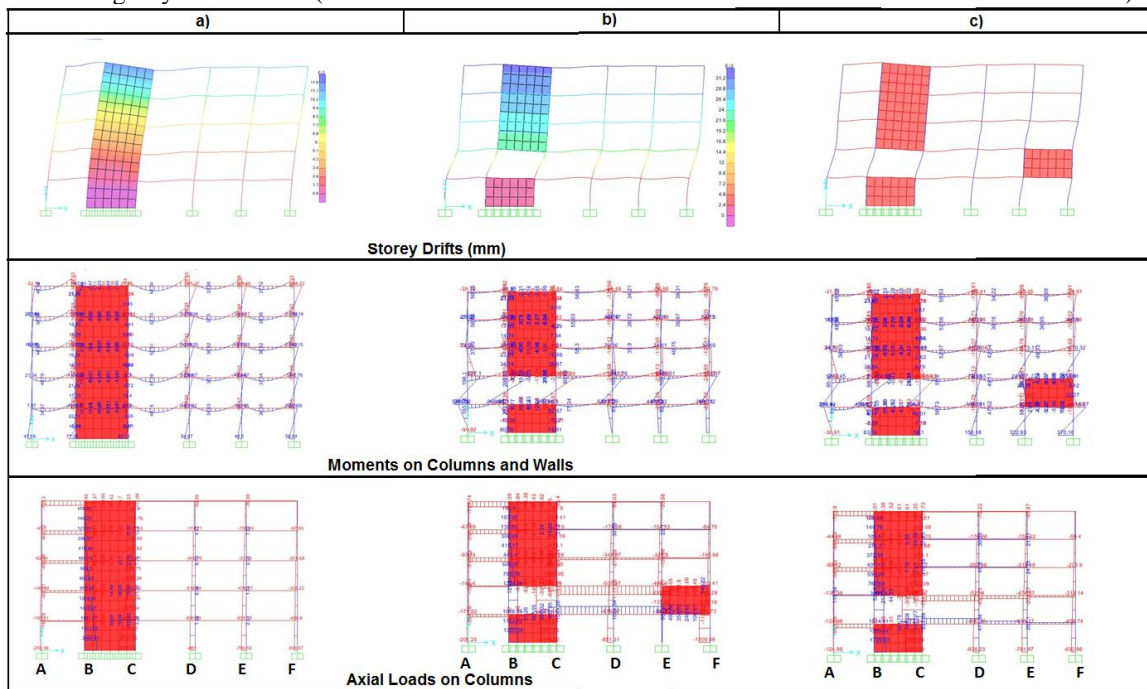

Figure 1 2D Frame: Deflections and stresses due to static seismic loads.

A similar increase does not exist in Case c), because although the wall 2 has been removed from the span B-C, but overall stiffness has been maintained since the same wall was repositioned on the E-F span. On the contrary, movements have a decrease in the order of -22.0%. A corresponding reduction was also observed in the shear forces (-35.3%) and moments (-40.1%). Finally, it is observed that the axial forces (a) of the two posts on the axes B and C in case of the interrupted wall and (b) the two pillars of the ground floor on the axes D and E in the case of the rearranged wall are getting great axial loads, which is expected because the wall above is "supported" on them. However, while in the case of the interrupted wall these pillars simultaneously develop very large moments, which is not the case for the case with rearranged wall (Case c).

1.2   *Analyzing Different Arrangements of RC Walls/Steel Braces*

In the previous section it was proven that discontinuous walls are advantageous for the retrofitting of existing building. In this section, it is discussed how to decide on the right arrangement of the discontinuous walls.

For this comparison exercise, a four floors by 7 bays frame will be adopted, with dimensions 3mx4m. The members used will be reinforced concrete columns with a cross section of $50x50cm^2$ and reinforced concrete beams with a cross section of $25x50cm^2$. The panels used will also be of reinforced concrete with a thickness of 20cm. The loads will be acting on each floor as illustrated on the figure below.
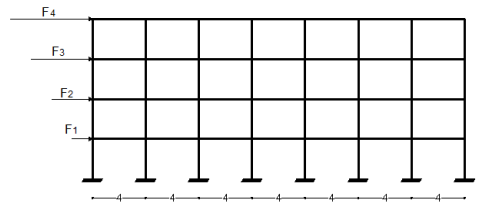
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Figure 2 Dimensions and loads acting on the frame under study

Level 1: F_1 =100 KN; Level 2: F_2 =200 KN; Level 3: F_3 =300 KN; Level 4: F_4 =400 KN

1.2.1 Wall Arrangement Cases

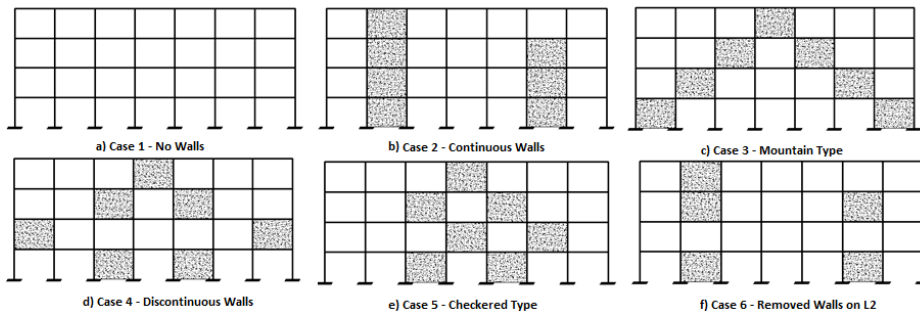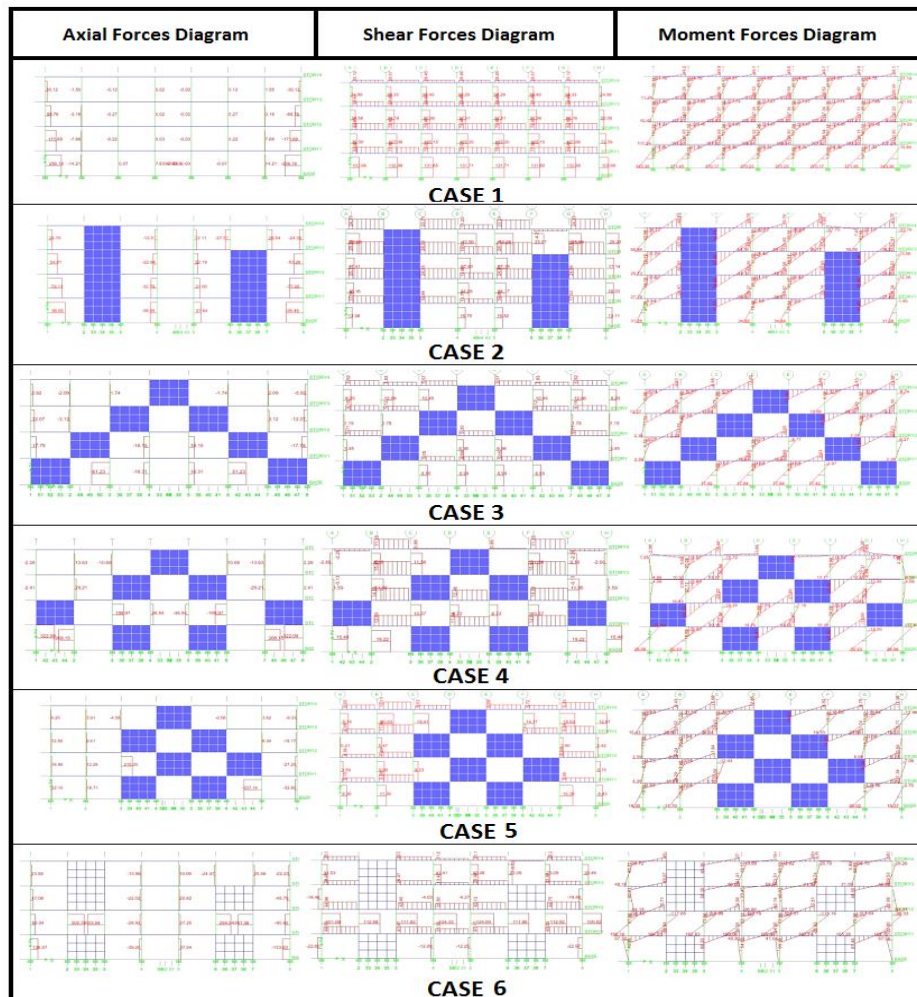The wall arrangement cases that will be considered in this paper are six, as illustrated in Figure 3.

Figure 3 Wall arrangement cases

1.2.2 Analysis Results

1.2.3   Assessment of Results

Horizontal floor shifts

Horizontal deflections of the floors for the building with discontinuous panels are 35-116% smaller than those of the continuous panels. Between the continuous wall (Case 2) and the interrupted wall (Case 6) cases there is an extremely large increase in the horizontal deflections (+ 379.0%) and in the internal forces for the elements on Level 2. This fact was, of course, to be expected, due to the sharp reduction in the rigidity of this level (creation of flexible - soft - floor due to its removal wall on the second floor).

Moment forces for columns and walls

On the ground floor, which is the most important level, the difference in its bending moments between cases with continuous and discontinuous walls is considerably high: approximately 400% greater bending moments are experienced in the case of continuous walls. This obviously has a great deal of practical significance, because the base moment directly affects the required dimensions of the foundations. Bending stress of the continuous walls is drastically reduced on the middle and high floors.

On discontinuous walls, the distribution of the bending moments is more even and the classical linear distribution of the continuous arrangement is not observed due to the frame wall coupling. This means that the structure works more as a whole – as one entity. In general, the bending moments on the discontinuous walls are about 50% of those on the continuous walls.

Shear and wall shear forces

The shear forces are not very different between the two cases, as it is illustrated in the figures in Section 1.2.2.

Axial forces of posts and walls

In general, the column axial forces are smaller for the continuous walls but this is opposed by the high moments in these columns. Practically high moments are those which dictate the reinforcement in a column. However, there is a negative impact from using

1.2.4   Conclusions

From the results that are presented in this section it can be seen that case 5 gives the most balanced results. This is because this option gives the smallest deflections for small moments on the foundations (ground floor) and the smallest columns axial forces amongst the cases with discontinuous walls.

1.3   Evolutionary Structural Optimization Method

In this section, a method that finds the optimal reinforcement method that will give the structure with the highest stiffness for the least material is given. This method is explained in more detail originally by Yang et al and is given in Ref [2] and is called the bi-directional evolutionary structural optimization (BESO) because it allows material to be removed and added simultaneously. This method removes the material that is not fully utilized for the resistance against the horizontal loads. The utilization of the material is checked by calculating the Von Mises stresses.

Topology optimization, as these methods are called, is often aimed at searching for the stiffest structure with a given volume of material. In this method, a structure is optimized by removing and adding elements. That is to say that, the element itself, rather than its associated physical or material parameters, is treated as the design variable. Thus, the optimization problem with the volume constraint is stated as

Minimize:
$$C = \frac{1}{2} f^T u \tag{1a}$$

Subject to:
$$V^* - \sum_{i=1}^{N} V_i x_i = 0 \tag{1b}$$

$$x = 0 \ or \ 1 \tag{1c}$$

where f and u are the applied load and displacement vectors and C is known as the mean compliance. V_i is the volume of an individual element and V^* the prescribed total structural volume. N is the total number of elements in the system. The binary design variable x_i declares the absence (0) or presence (1) of an element.

One of the aims of this new method BESO explained in Ref [2] is to make the algorithm to be stably convergent towards a solution which exactly addresses the above optimization problem statement.

1.3.1   Sensitivity Number

When a solid element is removed from a structure, the change of the mean compliance or total strain energy is equal to the elemental strain energy [3]. This change is defined as the elemental sensitivity number:

$$\alpha_i^e = \Delta C_i = \frac{1}{2} u_i^T K_i u_i \tag{2}$$

where u_i is the nodal displacement vector of the i_{th} element, K_i is the elemental stiffness matrix. When a nonuniform mesh is assigned, the sensitivity number should consider the effect of the volume of the element. In such a case, the sensitivity number can be replaced with the elemental strain energy density as:

$$\alpha_i^e = e_i = \left(\frac{1}{2} u_i^T K_i u_i \right) / V_i \tag{3}$$

The BESO procedure for stiffness optimization is directly driven by gradually removing elements with the lowest sensitivity numbers defined in Equation (2) or (3).

Here the principle of the BESO method is given as it is not the purpose of this paper to give a thorough explanation of the method. For more information refer to [2]. For the purpose of this paper the same 2D frame as in the previous section will be used to find the optimum walls/braces arrangement to reinforce a structure against seismic loads, or any horizontal loads.

1.3.2   Removing/Adding Elements Principle

With this method a volume constraint is given initially (V*) which is the target volume for the reinforcing material. Because with this method elements can be added or removed, the volume at the initial guess design can be greater or smaller than the volume constraint (V*). The evolution of the volume can be expressed as follows:

$$V_{k+1} = V_k (1 \pm ER) \Rightarrow (k = 1, 2, 3, ...) \tag{4}$$

where ER is the evolutionary volume ratio. Once the volume constraint is satisfied, the volume of the structure will be kept constant for the remaining iterations as:

$$V_{k+1} = V^* \tag{5}$$

Then the sensitivity numbers for all finite elements (solid and void) are calculated and sorted according to their numbers from the highest to the lowest. For solid elements (elements with binary design variable = 1), it will be removed (switched to 0) if:

$$\alpha_i \leq \alpha_{del}^{th} \tag{6}$$

For void elements (0), it will be added (switched to 1) if:

$$\alpha_i > \alpha_{add}^{th} \tag{7}$$

where α_{del}^{th} and α_{add}^{th} are the threshold sensitivity numbers for removing and adding elements, and α_{del}^{th} is always less than or equal to α_{add}^{th}. α_{del}^{th} and α_{add}^{th} are determined by the following three simple steps:

1. Let $\alpha_{add}^{th} = \alpha_{del}^{th} = \alpha_{th}$ thus α_{th} can be asily determined by V_{k+1}.
2. Calculate the volume addition ratio (AR), which is defined as the number of added elements divided by the total number of elements in the design domain. If $AR \leq AR_{max}$ where AR_{max} is the maximum volume addition ratio, the third step should be skipped. Otherwise recalculate α_{del}^{th} dhe α_{add}^{th} as explained in step 3.
3. α_{add}^{th} can be calculated by first sorting the sensitivity number of void elements (0). The number of elements to be switched from 0 to 1 will be equal to AR_{max} multiplied by the total number of elements in the design domain.

α_{add}^{th} is the sensitivity number of the element ranked just below the last added element. α_{del}^{th} is then determined so that the removed volume is equal to ($V_k - V_{k+1}$ + the volume of the added elements).

ARmax is introduced to avoid adding too many elements in a single iteration. Normally it is greater than 1% so that it does not hinder the advantage of the method of adding new elements.

The cycle of adding and removing finite elements continues until the objective volume (V*) is reached. However, also a convergence criterion needs to be satisfied:

$$\frac{\left| \sum_{i=1}^{N} C_{k-i+1} - \sum_{i=1}^{N} C_{k-N-i+1} \right|}{\sum_{i=1}^{N} C_{k-i+1}} \leq \tau \tag{8}$$

where k is the current iteration number, τ is an allowable convergence tolerance and N is an integer number. Normally, N is selected to be 5 which implies that the change in the mean compliance over the last 10 iterations is acceptably small.

1.3.3   Retrofitting 2D Frame With BESO Method

In order to compare the results of this method with the walls distributions that were presented in Section 1.2 a retrofitting strategy is assessed using BESO2D software. The BESO method is supposed to give the most efficient reinforcement against the seismic or any horizontal loads. The parameters inputted in the software are: ER = 2 %; r = 0.6; τ = 0.05 %; max no of cycles: 200; Volume: 30 %.

Firstly, a membrane (see in green in the figure below) is applied over the whole frame and discretized in finite elements. This membrane will be the subject of the method – removing and adding the finite elements that have the lowest stresses.
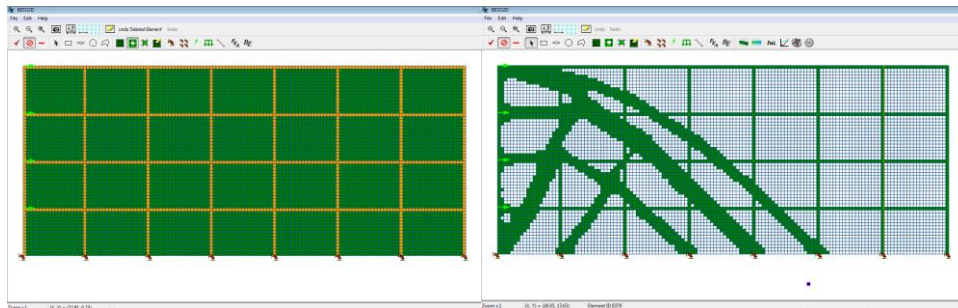

Figure 4 The optimization process using the BESO method on BESO2D software

Therefore, this method gives the locations where the RC walls or the steel braces would be most efficient in the structure. For the purpose of this structure steel braces have been used and the structure is analyzed in the ETABS structural software.
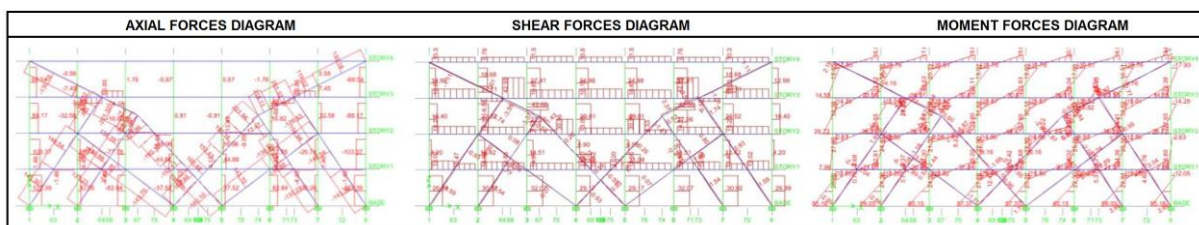

Figure 5 CASE 7 analysis forces

2   CONCLUSIONS

In Section 1.2 different wall arrangements were compared. It was observed that an even and regular distribution of walls or braces gives (Case 5 – checkered distribution of walls) better results for retrofitting an existing structure against horizontal loads. However, for larger structures it is important that more detailed analysis is carried out in order to find the best arrangement to save time and reduce costs. For this reason, the method BESO was adopted to find the optimal distribution of walls/braces (Case 7).

The results from the analysis for Case 5 and Case 7, have been summarized in the tables below for comparison. The results show that in Case 5 the displacements are lower but this comes at a cost of using more material. Also, the internal loads in the columns are much lower in Case 7 where the BESO method was used.

Both methods can be used depending on the situation. The findings in this paper suggest that for small structures a regular distribution of walls or braces can be adopted without detailed analysis. For larger structures, a BESO analysis could be carried out to find the most optimal and economical distribution of walls.

Table 1 Analysis forces and displacements for Cases 5 & 7

CASE 7						
Storey	Level [m]	Loading	Δx [cm]	$(\Delta x_i - \Delta x_{i-1})/h_i$	Qx [kN]	M [kNm]
4	12	Horizontal	0.39	0.000333	400	0
3	9	Horizontal	0.29	0.000400	700	1200
2	6	Horizontal	0.17	0.000300	900	3300
1	3	Horizontal	0.08	0.000267	1000	6000
0	0	Horizontal	0	0	1000	9000

$\Delta4/H = 0.0063/12 = 0.000525$

CASE 5						
Storey	Level [m]	Loading	Δx [cm]	$(\Delta x_i - \Delta x_{i-1})/h_i$	Qx [kN]	M [kNm]
4	12	Horizontal	0.15	0.000200	400	0
3	9	Horizontal	0.09	0.000100	700	1200
2	6	Horizontal	0.06	0.000100	900	3300
1	3	Horizontal	0.03	0.000100	1000	6000
0	0	Horizontal	0	0	1000	9000

$\Delta4/H = 0.0015/12 = 0.000125$

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