REGULARITY INDICES FOR BRIDGE STRUCTURES

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SUMMARY

A number of methods can be used for the analysis of bridge structures. Some of these methods are well known, and some of them have been developed recently (e.g. N2 method, based on the push-over analysis and inelastic spectra). It has been realised that the appropriate method of analysis and the level of structural model simplification strongly depend on the regularity of the bridge. In general, simplified SDOF models can not be used for the analysis of irregular structures. Since the criteria for the regularity of bridges is not always clearly defined, an attempt has been made to define regularity indices. These indices could be the criteria for the application of the simplified elastic (single-mode-spectral method) as well as simplified inelastic method (N2 method) for the analysis of bridge structures.

INTRODUCTION

Bridges give the impression of being rather simple structures, whose seismic response could be easily predicted. However, in recent earthquakes many of them have not performed well. Irregular behaviour has been one of the major reasons of this inadequate response.

Most of the modern codes for seismic design of bridges involve the wide range of methods for seismic analysis of bridges, from very simple elastic to very sophisticated inelastic methods. The main supposition in most of the simplified methods is that the ductility demand is uniformly distributed over the entire structure and that the single mode governs the response. Therefore, these methods can be used for the analysis of the so-called "regular" structures, only. However, the regularity of bridge is not clearly defined in most of the codes.

In recent years many research efforts has been devoted to problem of bridge regularity. Excellent work in this field has been carried out by Calvi [Calvi 1994, Calvi 1997], who introduced a regularity index with the objective of making it possible to predict whether or not a bridge will respond as expected in the preliminary design stage. This index is based on comparisons of the modal shapes of bridges and of the modal shapes of their decks alone. For the objectives that it was developed for, it is a very convenient tool. However, since it is based on the results of modal analysis, it cannot be used to assess whether or not the most simplified elastic method is applicable. Neither can it be used in the case of bridges with roller bearings at their abutments, which permit free movement of the deck in the transverse direction at these locations. For this case it is not possible to define the modal shapes of the deck alone. Therefore, an additional regularity index or the definition for the structural regularity is needed.

Recently, a new simplified inelastic method (N2 method), which is based on the push-over analysis, has been developed. It was found out that it could be used for the analysis of regular structures, only. To define the range of applicability of this method an index of regularity is also needed.

The problem of regularity was investigated within the parametric study of a simple idealised bridge. Several methods of analysis were used within this study. They are briefly described in the next section of this paper. Then two regularity indices are proposed. One of them could be used as the criterion for the applicability of the

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most simplified elastic method of analysis and the second one as the criterion for the applicability of the new simplified inelastic N2 method.

DESCRIPTION OF THE STUDY

Analysed structures

The issue of regularity and applicability of simplified analytical procedures was investigated by a parametric study in the transverse direction of an idealised viaduct (Figure 1). The same structural system was originally tested by Italian researchers [Pinto 1995, Pinto 1996]. The number of parameters was increased in comparison with the original study.

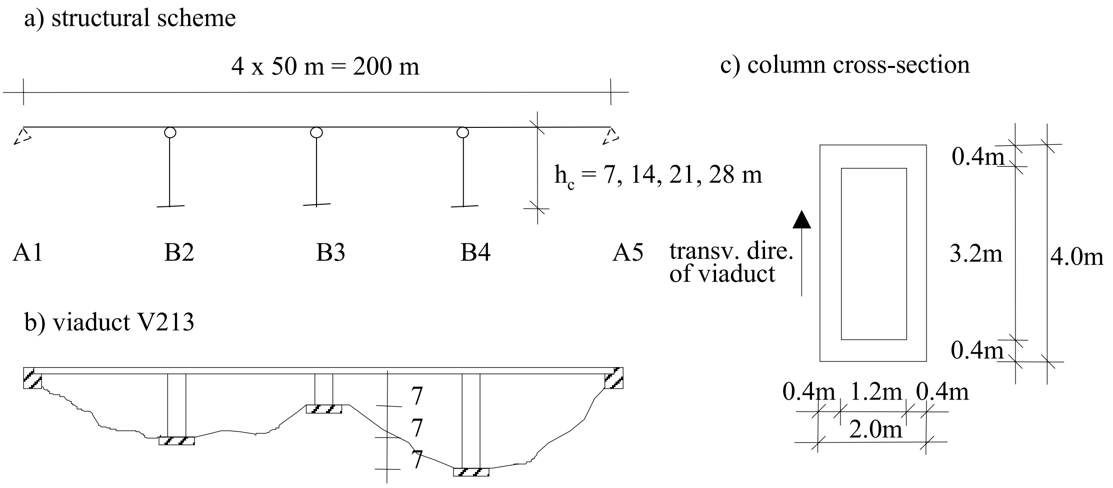


Figure 1. Layout of the investigated viaducts

Viaduct consisted of a 200-meter deck and three single column bents. The height of the individual columns (h_c) was varied (h_c = 7 m, 2 x 7 m, 3 x 7 m, and 4 x 7 m), resulting in 40 different combinations. For each combination, two extreme boundary conditions at the abutments were considered. In the first case it was assumed that the abutments were pinned in the transverse direction, whereas in the second case the roller supports at the abutment were assumed. In the paper these two cases are denoted as P and R viaducts.

All structures were analysed using elastic methods of analysis (see next subsection), first. Then 24 of them (considering P type and R type) were analysed using the inelastic methods of analysis, too. For each structure two different column reinforcements were considered. In one case the reinforcement in columns was determined based on the earthquake load in both, the longitudinal and the transverse direction of the bridge, while in the second case only the earthquake load in the transverse direction was considered. In the paper, these two cases are denoted as a "strong reinforcement" and "weak reinforcement", respectively. Since, the length of the end spans was found very important parameter influencing the response of the R-type viaduct, six additional structures with reduced end spans (length of 35 m) were also analysed.

Methods of analysis

In the presented study four methods of analysis were used: a) simplified elastic single-mode-spectral method (SM), b) elastic multi-mode-spectral-method (MM), c) simplified inelastic method (N2 method), and d) inelastic time-history analysis (IA). These four methods can be classified as it is shown in Figure 2. The levels of method sophistication are indicated with arrows.

The simplest method is the SM method. This is an elastic, static, iterative method, where the Rayleigh method is used for the estimation of the fundamental period of the structure. For the estimation of the first mode shape, the load f_i=m_ig (m_i is the lumped mass and f_i is the force at the node i) is applied, first. On the basis of the estimated shape of the first mode, the earthquake forces F_i are calculated. The structure is then loaded again by the forces F_i, and new displacements of the structure are obtained.

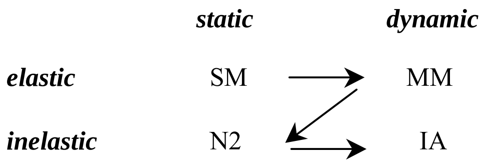


Figure 2. Classification of the used methods of analysis

The N2 method is a simplified inelastic method of analysis. This method combines the push-over analysis of the MDOF model of structure to estimate seismic capacity and local demand, and inelastic dynamic analysis of the equivalent SDOF system to estimate the global seismic demand [Fajfar 1996, Fajfar 1998]. Using the push-over analysis, a characteristic non-linear force-displacement relationship of the MDOF system is determined, first. In this phase the displacement shape of the structure has to be assumed, since it determines the distribution of lateral load. In the presented study the parabolic shape was assumed for P viaducts and the uniform distribution for the R viaducts.

Seismic load

In the elastic methods the design response spectrum as defined in Eurocode 8/2 [EC8/2 1994] for a design ground acceleration of $a_g = 0.35g$, medium soil conditions, and the highest level of ductility (behaviour factor $q = 3.5$) was used (Figure 3).

In the N2 method, inelastic spectra derived from the Eurocode 8/2 (EC8/2) design spectra were used. The 0.35g and 0.7g peak ground accelerations were considered.

In the inelastic dynamic analysis two artificial earthquake records (Figure 3) were used. They were generated on the basis of the EC8/2 design spectrum.

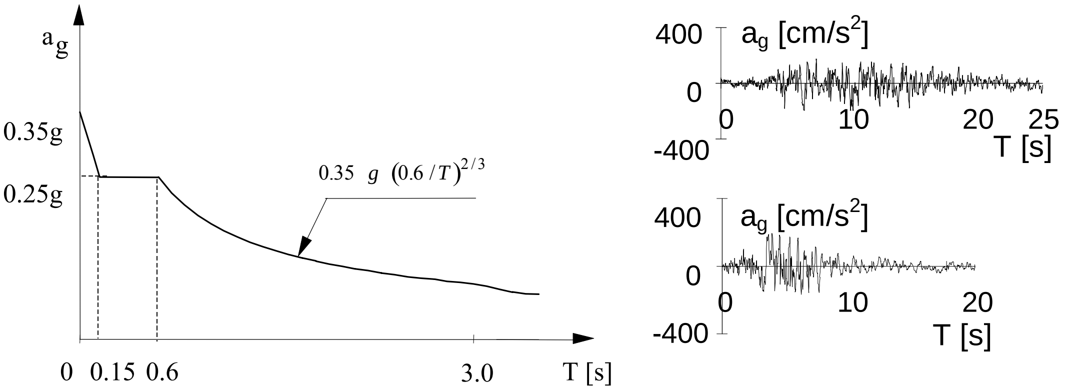


Figure 3. EC8/2 design spectrum and artificial accelerograms generated based on this spectrum

REGULARITY INDICES

The simplified methods (the SM method and the N2 method) can not be used for the analysis of irregular structures. Therefore, the criterion for bridge regularity (regularity index) is needed.

The response of the bridge strongly depends on the ratio of the deck stiffness and stiffness of the bents [Isaković 1999]. The stiffer is the deck, more regular the bridge is. This is due to one predominant shape of the bridge. The deck of the reinforced concrete bridge is usually designed to respond elastic to the strong earthquakes and its properties does not change significantly. On the contrary, columns are usually designed to withstand significant plastic deformations during the strong earthquakes. Therefore, the stiffness of the concrete columns can significantly change, based on their properties and the level of earthquake intensity. Consequently, the ratio between the deck stiffness and that of the columns can change during the time. When using elastic methods of analysis only one value for column stiffness could be assumed (usually that of the uncracked column), while in the inelastic analysis the changes of column stiffness could be modelled. Considering all these facts, two different criteria (two regularity indices) for the applicability of the SM and the N2 method were defined. In general, the definition of both indices is similar, although they are based on the results obtained by different method of analysis. In both cases the displacement shapes obtained within the two iterations of the method are compared. The proposed indices are described in the next subsections.

Index defining the range of applicability of the SM method

An index defining the applicability of the SM method is based on the comparison of the displacement shapes obtained within the first and second iteration of the SM method. The procedure is schematically presented in the Figure 4. Displacements obtained within the first iteration are based on the acceleration of 1.0g. Therefore, they are normalised considering the acceleration $S_d(T)$ in the design spectrum corresponding to the estimate period of the structure T (displacements are multiplied by the ratio $S_d(T)/g$).

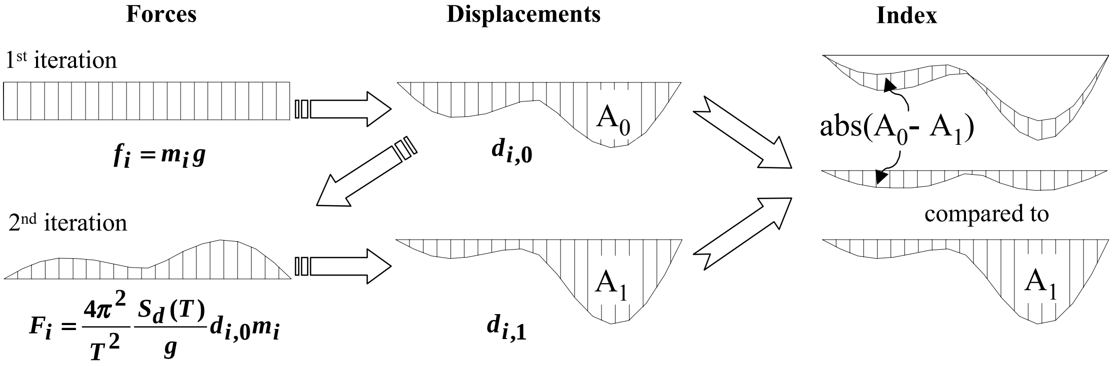


Figure 4. Scheme of the SM method and definition of the proposed index

The index is calculated as the relative difference between the areas bounded by the displacement lines of the 1st and 2nd iteration (see Figure 4) of the SM method. When the displacements are calculated at the equidistant nodes, the index can be expressed as:

a) P viaducts

$$index = \frac{|A_0 - A_1|}{A_1} = \frac{\sum_{i=1}^{n-1} |d_{i,0} - d_{i,1}|}{\sum_{i=1}^{n-1} |d_{i,1}|} \cdot 100 \ \ [\%] \qquad [1]$$

b) R viaducts

$$index = \frac{|A_0 - A_1|}{A_1} = \frac{\frac{1}{2}|d_{0,0} - d_{0,1}| + \sum_{i=1}^{n-1} |d_{i,0} - d_{i,1}| + \frac{1}{2}|d_{n,0} - d_{n,1}|}{\frac{1}{2}|d_{0,1}| + \sum_{i=1}^{n-1} |d_{i,1}| + \frac{1}{2}|d_{n,1}|} \cdot 100 \ \ [\%] \qquad [2]$$

The parameters in formulas [1] and [2] are defined in Figures 4 and 5. The index is expressed in %, therefore the value is multiplied by 100.

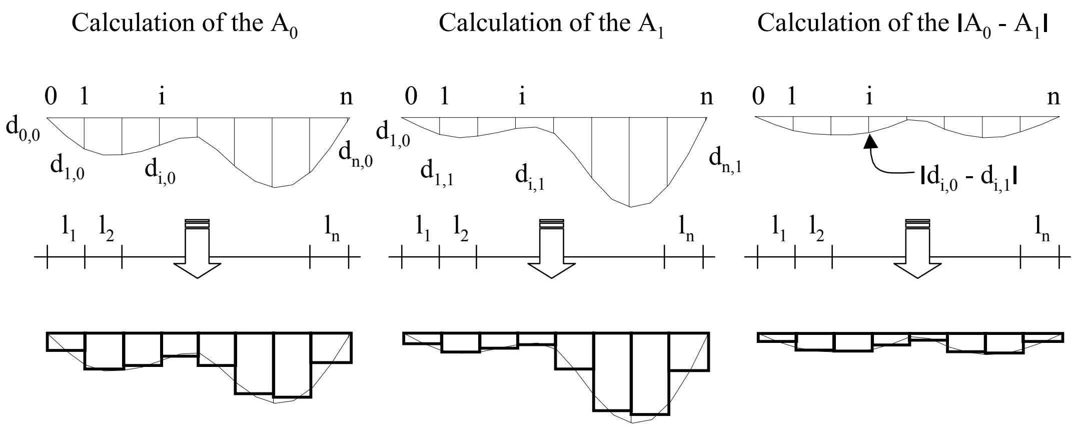


Figure 5. Calculation of the proposed index

The proposed index was evaluated comparing the results of the SM and the MM method. The difference in the response obtained with these two methods was defined as the relative difference of areas bounded by the envelopes of the relevant displacement lines. These areas and their relative difference were calculated in the same way as in the case of index (see Figure 5).

The relative differences between the SM and MM method (for all analysed structures) as a function of the proposed index are presented in Figure 6. The very good correlation of 0.96 was obtained.

The greater is the value of the index, the difference between two methods is greater and structure is more irregular. It is evident form the Figure 6 that the R viaducts are in general much more irregular than P viaducts. Even some symmetric R viaducts were found to be irregular. Mainly the great length of the end spans causes the irregularity of these structures. The detailed analysis of the most important parameters causing the irregularity of structure could be found in [Isaković 1999].

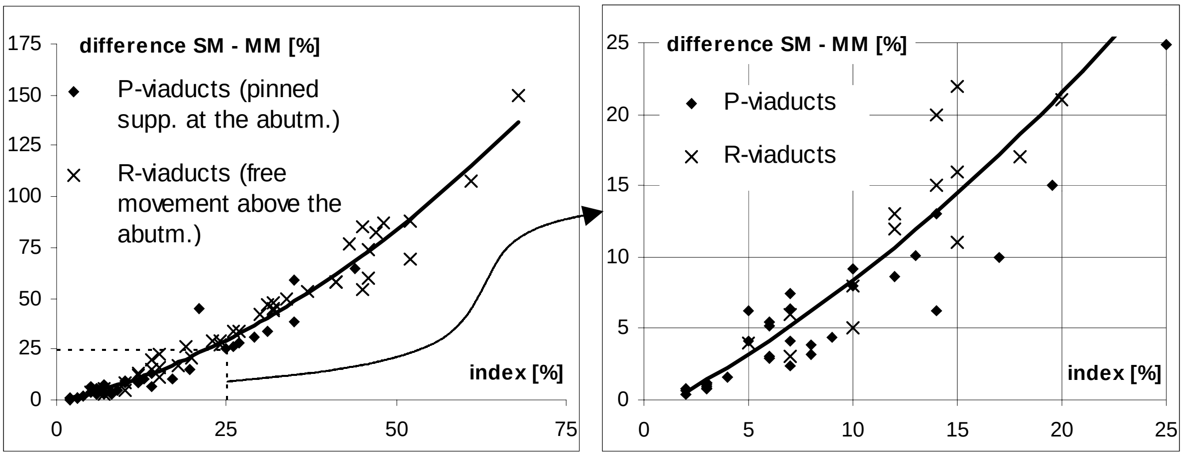


Figure 6. Difference between the SM and MM method in function of the proposed index

Index defying the range of applicability of the N2 method

An index, which defines the applicability of the N2 method, was determined in similar way as one for the SM method (see Figure 7). Two displacement shapes were compared. The first one was determined with the N2 method. To obtain the second displacement shape, push-over analysis of the MDOF model was repeated with the new distribution of the lateral load, up to the maximum displacement determined with the N2 method (see Figure 7). The new distribution of lateral load was based on the displacement shape obtained with the N2 method. In both cases displacements were normalised to the maximum displacement of the superstructure. The proposed index is calculated as the relative difference of areas bounded by the described displacement shapes. Note that absolute values of displacements were taken into account.

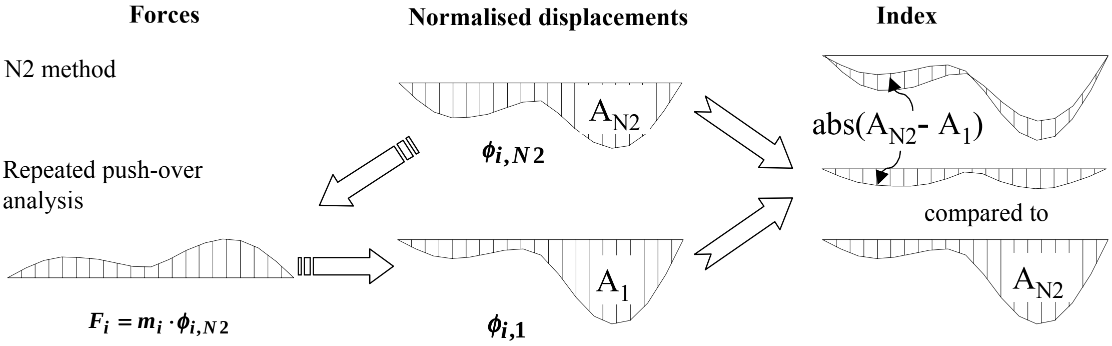


Figure 7. Definition of the proposed index

The areas are calculated in the same way as in the case of index for SM method (see Figure 5). When displacements are calculated at the equidistant nodes the index can be expressed as:

a) P viaducts

$$index = \frac{\left|A_{N2} - A_1\right|}{A_{N2}} = \frac{\sum_{i=1}^{n-1}\left\|\phi_{i,N2}\right| - \left|\phi_{i,1}\right\|}{\sum_{i=1}^{n-1}\left|\phi_{i,N2}\right|} \cdot 100 \;\; [\%] \qquad [3]$$

b) R viaducts

$$index = \frac{\left|A_{N2} - A_1\right|}{A_{N2}} = \frac{\frac{1}{2}\left\|\phi_{0,N2}\right| - \left|\phi_{0,1}\right\| + \sum_{i=1}^{n-1}\left\|\phi_{i,N2}\right| - \left|\phi_{i,1}\right\| + \frac{1}{2}\left\|\phi_{n,N2}\right| - \left|\phi_{n,1}\right\|}{\frac{1}{2}\left|\phi_{0,N2}\right| + \sum_{i=1}^{n-1}\left|\phi_{i,N2}\right| + \frac{1}{2}\left|\phi_{n,N2}\right|} \cdot 100 \;\; [\%] \qquad [4]$$

The parameters in formulas [3] and [4] are defined in Figure 7. In previous equations index is expressed in %, therefore the value was multiplied by 100.

The index was evaluated comparing the results of the N2 method with the results of the inelastic time history (IA) method. Normalised displacements obtained with both methods were compared. The difference was defined as the relative difference of areas bounded by these displacement shapes.

The relative differences between the N2 and IA method as a function of the proposed index are presented in Figures 8 and 9. The results are analysed for P and R viaducts separately. For P viaducts the correlation of 0.98 was obtained, while for the R viaducts the correlation was lowest (0.91) and the dispersion of results was larger. In both cases the extreme results were excluded from the analysis (for P viaducts 1, and for R viaducts 3 results).

It is evident from the Figure 8 that most of the P viaducts are regular and the N2 method can successfully predict their response. Viaducts with "weak reinforcement" are more regular than those with the "strong reinforcement". When structures are subjected to the stronger earthquake, their behaviour is, in general, more regular.

In general, the response of the R viaducts is more irregular than response of the P viaducts. The differences between the N2 method and IA method are considerably larger than in the P viaducts. The R viaducts with the very long end-spans can respond irregularly even if they are symmetric. However, when the length of the end-spans in R symmetric structures is reduced (the more realistic and usual case) the behaviour is significantly more regular. The asymmetric R structures are in general irregular. They could be torsionally very sensitive. For this type of structures the N2 method has to be used with care.

The displacements of the deck at the top of the columns and above the abutments are essential for the response. Therefore, the proposed index was recalculated using the normalised displacements at this nodes, only (see Figure 10). The results are similar and the conclusions are the same as in the case of the previous calculations of the index.

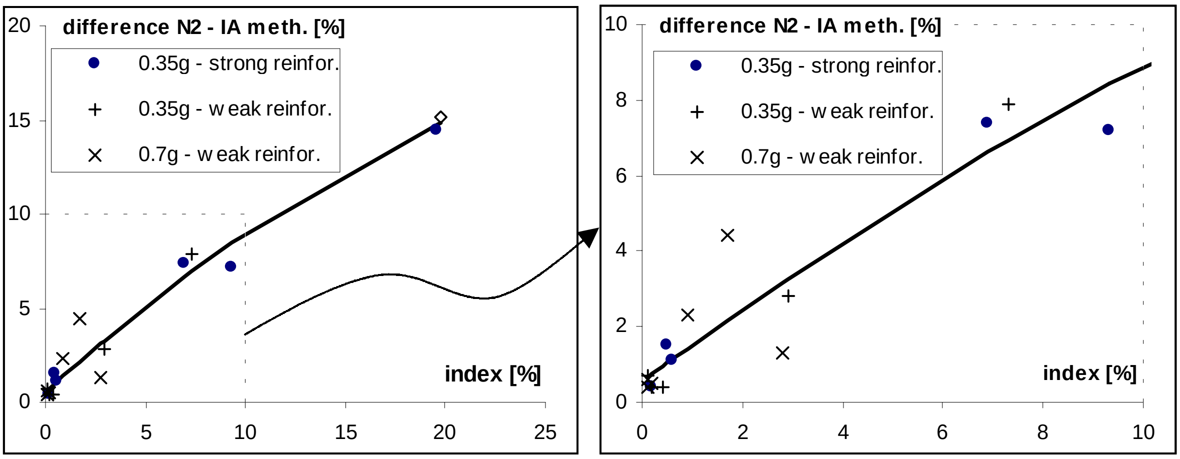


Figure 8. Difference between the N2 and IA method in function of the proposed index (P viaducts)

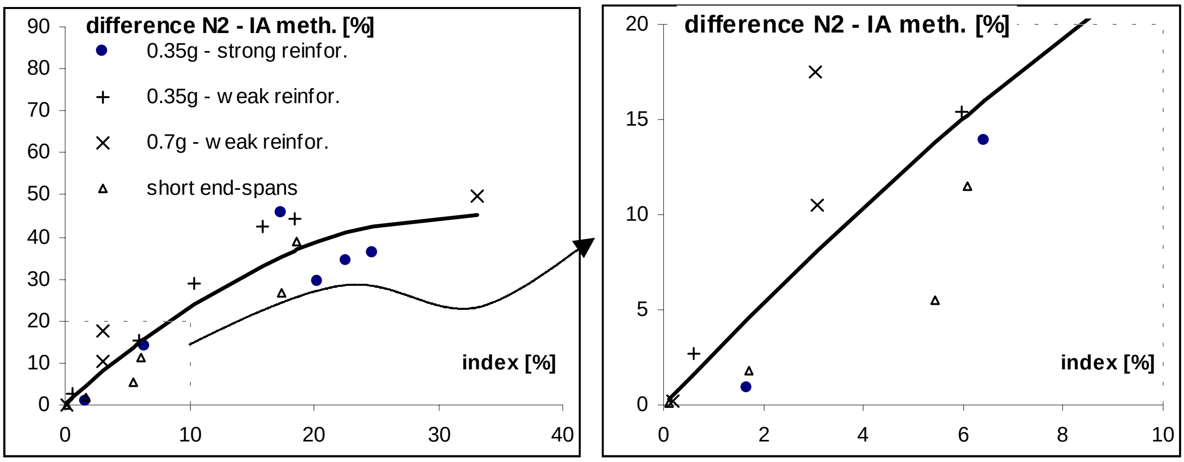
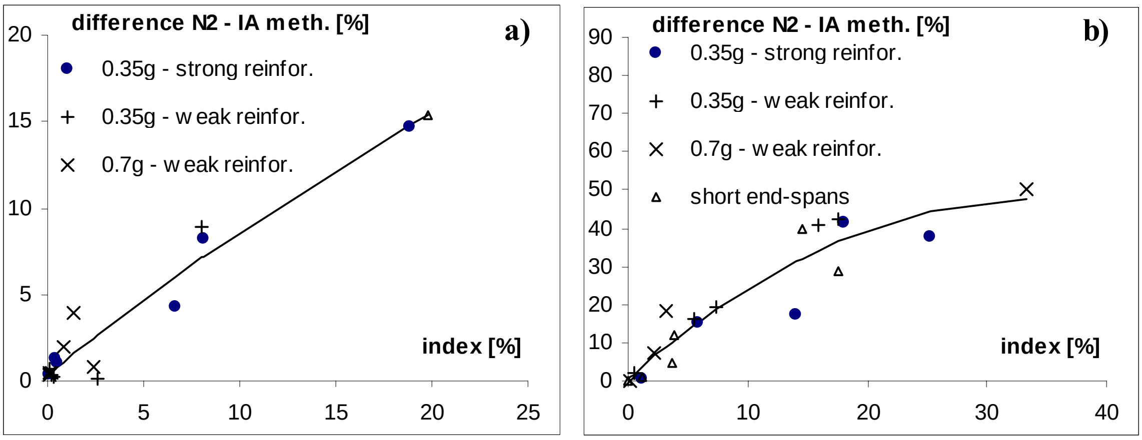


Figure 9. Difference between the N2 and IA method in function of the proposed index (R viaducts)



a) P viaducts (pinned supports at the abutments) b) R viaducts (free movements above the abutments)

Figure 10. The proposed index, calculated based on the normalised displacement at the top of the columns and above the abutments

CONCLUSIONS

The two regularity indices for bridges are proposed in the paper. One could be used as the criteria for applicability of the simplified elastic single-mode-spectral method and the other as the criteria for applicability of the simplified inelastic "N2" method. The definition of both indices is similar, although they are based on the results obtained by different method of analysis. In both cases the displacement shapes obtained within the two iterations of the appropriate method of analysis are compared.

Using the proposed indices it is concluded that the simplified static methods can not predict the behaviour of the irregular structures well. The irregularity of the structure depends on the properties of the structure as well as the intensity of the earthquake load. In general, the viaducts with roller supports at the abutments are more irregular than the viaducts with pinned abutments. The viaducts with roller supports at the abutments and with very long end-spans can respond irregularly even if they are symmetric. However, when the length of the end-spans in such symmetric structures is reduced, the behaviour is significantly more regular. The asymmetric structures with roller supports at the abutments are in general irregular. For this type of structures the simplified methods have to be used with great care.

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