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Definition of one empirical model so as to review safety factors used in structural design and analysis

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Abstract— In the design phase structures generally are designed according to their strength capacity and should ensure proper service during its lifetime. The structural calculation is made from a certain material and considering loads and overloads. Due to the uncertainties in the construction processes and even when the necessary tests are performed, it is necessary to use safety factors that enable encompass the effect of these "imponderables".

In the case of bridges and viaducts, before being put into service, is mandatory to check the correct operation of the structure from the "load tests". In them, especially in static load tests, vertical displacements of significant points of the structure are compared. In this way, the vertical displacements measured are compared with those obtained with the structural analysis are compared; and recovery of its original geometry.

The present research focuses on the comparison of both results of load tests in different structures for a statistical study to define a confidence interval of the difference of vertical displacements and its possible extrapolation to the safety factors used according to the regulations that may apply. Discussed, thus the possible reduction of these coefficients with the consequent economic savings in the construction of such structures.

***Keywords*—structural monitoring, geometric control, load tests, geometric leveling.**

I. Introduction

The commissioning of a bridge, viaduct or footbridge is performed provided it overcomes a mandatory load test in which it is confirmed that their behavior corresponds to the projected and it resists the loads for which it was calculated.

When one structure is calculated some coefficients are used in order to claim that it is strong enough. These coefficients try to include possible uncertainties that could have happened during the construction process.

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In static load tests vertical movement of notable points are compared: that obtained by de structural analysis to that measured in de load test. Measurement is usual performed using geometric precision leveling, made with digital levels that allow to get a measurement accuracy of 1mm/km or better.

In this sense, this article aims to define a statistical model of the observed differences in load testing if, with modern methods of quality control during construction, the safety factors used could be rethought. This would result in a significant cost savings to both countries and administrations or individuals who defray these works.

II. Phases of a load test.

A. *Definitión of load test.*

Load tests are made following their own regulations or, failing that, following some recommendations for their implementation. Basically they consist in checking the structural behavior of bridge that has been completed. In this case the static load tests will be studied because the dynamics are intended to determine the frequencies of the structure analysed.

In order to make a load, it is drafted a project that studies the behavior of the structure through various load stages, that is, different placements for loads on the structure seeking the utmost stress in certain sections. Since the structure is designed with an elastic behavior it must be measured both the vertical movement and recovery of the original geometry, and checking cracking that could appear. The project of the load test will include all structural calculations, expected vertical movements of certain points of the structure and all the drawing that could be necessary.

Overloading is usually materialized by work trucks loaded with a certain weight and, therefore, they must all be weighed before the load test begins. Their type and placement must be defined in the project of the load test.

B. *Signposting the structure*

From the definition of the load test, before making it, it is necessary to mark all the points over the structure that are going to be measure and the situation of each truck for each load stage.

Placing trucks will be staked by topographic methodologies and must be marked, usually by painting, at least the ends of the truck axles. In this way, it is ensured both its position and its direction. Since the number of load stages can be large it should be used paint of different colors in order to allow to distinguish the placement of the truck for each load stage.

The points, at the vertical movement of the structure is going to be control, are objectified with spherical head nails permitting geometric leveling.

These points are those that are defined in the draft load test, generally vain centers and over supports, and allow to control the deformation of the structure due to bending stress and torsional stress.

Figure 1. Nails for gemetric leveling.

It is also important to underline that at least one point outside the structure will be objectified and it will serve as a fixed point in which the geometric leveling is based in order to begin and end it.

Figure 2. Detail of the markers of the structure.

C. Topographic instrumentation.

The static load tests conducted by topographic surveying are made from geometric leveling. The level used will have characteristics that ensure sufficient accuracy for the execution of the load test. In this respect, existing regulation normally gives an order of magnitude of the required accuracy.

Figure 3. Leica level DNA03.

Hoy Nowadays, it is common practice to use high-precision digital levels. Specifically, in the cases studied in this research an electronic level Leica DNA03, defined as having the following technical specifications, was used:

- Precision 1km double leveling:0.3mm
- Telescope magnification: 24x.
- sensitivity of level: 0.3"

D. Develpment of a load test.

The development of a load test is divided into various geometric leveling, starting at a fixed point outside of the structure, passes through all the points needed to level and ends at the starting point, in general. In all cases, it is leveled by the midpoint method for which it is necessary to mark previously the placements of the level. For this purpose some espainted marks are made measuring with a tape.

One load test is divided in different load stages. Thus, after an initial leveling over the empty structure, trucks are introduced into the previously marked positions, and after stabilization of the structure one topographer proceeds, again, to level it. Since the behavior of the structure should be in the elastic range, proceed to level the structure again after the withdrawal of the trucks and once stabilized it and thus the recovery of the structure can be controlled.

The process is repeated for each of the load stages and if it is necessary to use more than a day to run the day always ends with the structure without trucks, and the next day one leveling will be made without trucks too.

In all cases the weather conditions, especially the temperature will be check in order to control possible variations in the geometry of the structure due to they. However, it is important to note that the thermal inertia of the structure along with the limited time that normally requires a leveling make their influence generally negligible.

E. Safety coefficients.

In the structural calculation the different regulations establish safety coefficients that reduce the strength of the materials used and make greater the loads so as to calculate the structure in the ultimate limit states.

In case of calculation of the movements of a load test is not necessary to use these coefficients since it is considered as a limit state of use.

In this research the comparison of vertical movements between the calculated and the measured has been used as a parameter that allows to extrapolate the results to these coefficients so they can be discussed.

Since all cases studied correspond to structures in Spain these coefficients, defined in the legislation for this country, are presented.

TABLE I. SAFETY COEFFICIENTS IN SPAIN

Safety Coefficients		
Material	***Reduction of Value***	***Level of control***
steel	1.15	Reduced +0.05
		Typical +0
		Strong -0.05
concrete	1.5	Strong -0.1
		Rest of the cases +0
Load	***Increase of Value***	***Level of control***
Load	1.6	Reduced +0.2
		Typical +0
		Strong -0.1

III. Methods and foundation.

In this research data are referred to several load tests corresponding to different types of structures: beams mounted on two supports with precast beams, continuous concrete beams, continuous beam mixed, etc. Some of them have fleet angle or are curve.

In all the studied structures it was calculated the difference of the obtained vertical movement of structural analysis, contained in the draft load test, and the measured movement from the load test. Points studied were those in which there is some sort of vertical movement, regardless of direction, excluding therefore, those which are on the supports. In general, these points correspond to the mid-span, however there have been structures in this work, which have points at quarter span.

Due to heterogeneity of the total vertical movements and to have a more reliable parameter for comparison, it has been used the percentage difference between the vertical movement differences and the theoretical movement relative to the theoretical.

TABLE II. STUDIED STRUCTURES

Name	Number of span bridge	Length of span (m)	Structural typology	Material
Flyover 1 Guarnizo	1	16	prefabricated beams mounted on 2 supports	concrete
Flyover 2 Guarnizo	1	16	prefabricated beams mounted on 2 supports	concrete
Structure 1 Guarnizo	4	37-50-50-37	continuous beam	mixed steel-concrete
Marín	7	57.3-96-96-96-96-96-57.5	continuous beam	concrete
Mazmela	5	57.3-96-96-96-57.3	continuous beam	concrete
Zarimut	6	47.3-97.2-97.2-97.2-97.2-47.3	continuous beam	concrete
Flyover 122	1	30	continuous beam	concrete
Flyover 117.7	3	17-25.9-17	continuous beam	concrete
Flyover 119.1	3	14.2-25.9-14.2	continuous beam	concrete
Pujayo	5	60-100-100-100-60	continuous beam	concrete

Comparison of results has been performed in each structure individually, for which the average and standard deviation have been calculated for each load stage and after that the weighted average of the percentage differences and the standard deviation of this average have been estimated considering all load stages.

Finally structures have been grouped according to their type to obtain the percentage confidence interval of the differences in vertical movements for each of them. The clustering was performed similarly to the previous case, that is, assigning weights to each of the structures and calculating the weighted average and the standard deviation thereof.

In all cases the assigned weights are obtained from the variance according to the expression:

$$P_h = {}^{1}/_{S^2} \quad (1)$$

Where S^2 is the variance of the load stage h or of the structure as appropriate.

The weighted average is calculated using this formula:

$$\bar{x}_{WA} = \frac{\sum \overline{X_i} \cdot P_i}{\sum P_i} \quad (2)$$

The standard deviation of the weighted average will be calculated from the expression:

$$S_{WA} = \sqrt{\frac{\sum(\bar{x} - \overline{x_{WA}})^2 \cdot P_h}{(n_h - 1) \cdot \sum P_h}} \quad (3)$$

Where n_h is the total number of load stages or structures and $\overline{x_{WA}}$ is the weighted average.

Because the average value obtained for a given structural type is distributed according to the statistical Student, the resulting confidence interval will be obtained applying the formula:

$$\left[\bar{x}_{WA} - t_{n-1}\left(1 - {}^{\alpha}/_{2}\right)\frac{S_{WA}}{\sqrt{n}}, \bar{x}_{WA} + t_{n-1}\left(1 - {}^{\alpha}/_{2}\right)\frac{S_{WA}}{\sqrt{n}}\right] (4)$$

Therefore, the confidence interval depends on the weighted average and its standard deviation, the number of sample values (n) and a certain statistical confidence level ($t_{n-1}\left(1 - {}^{\alpha}/_{2}\right)$).

With this expressions the trend ,which could cause those points with a small vertical movement and that percentage could lead to large differences in the measured movement, is prevented. This may be due to various situations outside the studied phenomenon such as measurement accuracy, etc.

IV. Results.

Operating according to the expressions and development followed in the previous section, all statistics and confidence intervals have been calculated for all structures as it is reflected in Table II.

Since different structures contain in its draft load test a variable number of load stages as well as measuring points, only full results for the structure called "Pujayo" are presented because it is the longest of the studied structures and have a larger number of measured points, 30.

TABLE III. DIFFERENCES OF VERTICAL MOVEMENTS FOR "PUJAYO"

Percentage of differences between measured vertical movements and calculated						
Hyp. 1	**Hyp. 2**	**Hyp. 3**	**Hyp. 4**	**Hyp. 5**	**Hyp. 6**	**Hyp. 7**
22.3	35.8	810.5	30.7	33.5	56.7	92.3
22.2	34.0	43.3	34.0	28.7	41.1	85.2
24.6	33.6	60.8	35.9	28.5	63.6	74.7
45.9	40.7	33.9	34.4	36.6	31.2	85.2
45.7	36.3	28.8	28.6	33.5	38.7	92.3
44.9	42.8	36.8	36.9	41.5	31.4	75.9
31.8	34.7	44.8	34.9	28.9	32.6	97.8
26.7	36.0	43.9	27.5	22.1	35.5	2.9
30.5	35.7	46.3	35.6	28.8	36.1	38.9
45.5	39.8	36.5	43.8	26.0	37.6	47.5
48.5	34.3	37.6	40.7	24.3	37.7	50.9
52.1	41.3	35.2	41.4	29.7	43.5	53.8
13.7	32.9	61.2	41.0	54.1	75.4	57.5
15.4	35.5	58.1	43.7	48.2	5.8	0.8
15.5	37.5	64.9	42.5	44.7	30.0	35.6
28.1	47.0	47.5	47.9	39.6	71.5	16.5
28.9	46.2	46.0	46.5	41.3	72.6	16.4
26.0	46.4	52.7	47.5	34.6	46.7	4.1
48.2	38.1	38.6	44.9	48.0	40.0	70.0
49.6	52.8	39.6	43.8	41.8	37.0	60.5
45.5	37.9	42.0	42.4	52.4	37.5	56.6
36.6	43.3	45.8	37.0	46.1	45.3	58.1
33.5	41.5	44.4	32.9	35.5	47.4	61.7
38.1	43.9	44.9	34.3	43.3	56.6	61.1
42.3	41.5	41.8	30.2	32.6	36.3	63.1
46.6	39.4	38.3	34.6	29.3	37.2	68.0
42.3	40.3	40.6	34.2	19.6	35.1	66.5
39.9	45.3	42.0	41.6	54.8	73.2	65.0
34.5	43.8	70.8	41.1	45.3	67.9	68.9
35.2	44.1	32.2	41.5	47.4	64.5	65.9

It is noteworthy that in all structures it has been found that the vertical movement of the points is less than that from the structural calculation, but in the same direction, and therefore the results are shown in absolute value, disregarding the sign criteria according to the upward or downward movement.

For these percentage differences mean and standard for each of the charge states deviation is calculated.

TABLE IV. MEANS ANDA STANDARD DESVIATION FOR EACH STATE OF LOADING

	State of loading							
Name	H. 1	H. 2	H. 3	H. 4	H. 5	H. 6	H. 7	
Flyover 1 Guarnizo	42.7	40.8	39.1					Average
	12.5	11.1	4.0					Stand. desv.
Flyover 2 Guarnizo	31.6	25.1	35.0					Average
	11.5	17.0	8.4					Stand. desv.
Structure 1 Guarnizo	34.1	34.4	49.9	31.5	42.8	41.0		Average
	7.6	8.8	13.0	6.9	22.3	21.6		Stand. desv.
Marín	9.4	8.4	10.6	6.7	4.9			Average
	4.9	3.9	12.1	3.7	4.7			Stand. desv.
Mazmela	11.6	11.7	17.7	10.2	10.6			Average
	2.8	2.0	11.4	3.3	3.3			Stand. desv.
Zarimut	11.4	13.7	21.1	9.2	16.5			Average
	4.6	1.6	16.1	6.2	17.7			Stand. desv.
Pujayo	35.3	40.1	44.8	38.4	37.4	45.5	56.5	Mean
	11.1	4.8	10.0	5.7	9.8	16.3	26.4	Stand. desv.

Flyovers that do not appear in Table IV have only one measuring point so that only their statisticians are shown for the structure as a whole.

Calculating averages and standard deviations for each whole structure employing formulas (2) and (3) the following values are obtained:

TABLE V. GLOBAL STATISTICAL DATA FOR EACH STRUCTURE

Structure	**Weigted average**	**Standard desviation**
Flyover 1 Guarnizo	39.533	0.759
Flyover 2 Guarnizo	32.623	2.375
Structure 1 Guarnizo	35.292	2.411
Marín	7.443	0.804
Mazmela	11.338	0.491
Zarimut	13.313	0.699
Flyover 122	53.823	0.003
Flyover 117.7	36.945	7.307
Flyover 119.1	29.507	14.885
Pujayo	39.823	1.280

In order to obtain more representative values the structures have been grouped according to their structural type. Besides, confidence intervals at a level of 95%, 99% have been calculated.

TABLE VI. CONFIDENCE INTERVAL FOR STRUCTURAL TYPOLOGY

	Weigted average	**Standard desviation**	**Confidence interval**	
Flyovers	38.8	4.3	(33.9 ,43.7)	**95%**
			(31.1 , 46.4)	**99%**
Continuos Beams	13.2	4.5	(7.0 , 19.4)	**95%**
			(2.99 , 23.44)	**99%**
Mixed structures	35.3	2.4	(33.4 , 37.2)	**95%**
			(31.9 , 38.8)	**99%**

V. Discussion.

The first line of discussion of this research focuses on the nature of the data collected for comparison of vertical movements. In this work we have neglected those points which a priori would present a very small movement, the order of accuracy of the measurements, for example the points located on supports. However, in some structures and some load stages some points with a very small movement have been able to exist so that a small variation from expected produces a large percentage change. In this regard, flyovers can be seen as vertical movements are significantly lower than those calculated.

Throughout this work it was found that, without exception, all points have presented under vertical movements fewer than expected but always in the same direction, that is, if at one point the structure rose in the calculation so did and vice versa. That is why the sign has been removed from all movements, comparing them in absolute value.

As for the results, from those reflected in Table IV and Table V, it can be seen as differences in vertical movements are very similar regardless of the load stage. Therefore, they depend on the studied structure. However, to avoid the possible influence of a particular work, the structures have been chosen made in different places and at different times. Only the structure "flyover 119.1" presents a significant dispersion in the observed differences, which is justified by the existence of a single measuring point and only three load stages, thus the results it can be described as inconclusive .

When all the structures are considered grouped by their structural typology the results should not show any trend due to one specific bridge. Thus, as it is shown in Table VI, it can be seen for flyovers, with short spans, the differences between expected and measured vertical movements are around 30%. In this way, confidence intervals, both 95% and 99%, give its lowest value above this percentage. That is why extrapolating the results to the safety coefficients used in the structural analysis, it can be said that these coefficients could be reduced by 30%, especially if they have been made with prefabricated beams where control is stronger.

In case of continuous beams, the dispersion that have been found is greater if we compare it with de average. However, and for a confidence level of 99%, safety coefficients may be reduced by 3%. This value, although low, can be a significant cost savings because such structures often present significant lengths of span and their cost is quite higher.

Finally, in the case of mixed structures it has been found a possible reduction in safety coefficients of about 30%. However, this case has been studied by a single structure so this value should be taken with reservation to avoid potential dependencies of the structure.

In any case, this investigation is ongoing in order to incorporate as many structures as possible and then the sample will be larger for any structural type, including, if possible, new structures of different types.

VI. Conclusions.

The main conclusion of this work, that is manifested by the results, is the possible revision of the safety coefficients used in the calculation of structures, since the materials, construction methods and control have been a breakthrough on quality over the years .

This research proposes the definition of different coefficients depending on the structure type and they can be further reduced in those simpler structures and to a lesser extent those that have larger spans.

TABLE VII. VARIATION IN SAFETY COEFFICIENTS

Variation in Safety Coefficients	
Typology	***Reduction of Value***
Flyovers. Span<30m	-30%
Continuous beam. Span <100 m	-3%

However, the limited number of structures indicates that it is necessary the continuation of this research following this line of study and, therefore, these values may vary. In any case, what we can say is that these coefficients can be reduced since in all time points studied the measured value of the vertical movement has been less than expected which can result in significant cost savings.

References

[1] Ministerio de Fomento, Dirección General de Carreteras. "Recomendaciones para la realización de pruebas de carga de recepción en puentes de carretera". ISBN: 84-498-0425-6

[2] Ministerio de Fomento, Gobierno de España. "EHE-08 Instrucción de Hormigón Estructural". NIPO: 161-11-150-2.

[3] González Manteiga, M. "Modelos matemáticos discretos en las ciencias de la naturaleza" Editorial Santos. ISBN: 84-7978-550-0

[4] Ferrer Torio, R., Piña Paton, B., De Luis Ruiz, J.M., Ruiz Bedia, M.L., Castillo López, E., "Geodetic Deformation Monitoring: From Geophysical to Engineering Roles", International Association of Geodesy Symposia, Vol. 131, 2005, pp. 270-276

[5] García Páez, A., Navarro Veguillas, H., Vélez Ibarrola, R., "Estadística II" Universidad Nacional de Educación a Distancia ISBN: 84-362-3154-6.

[6] Chueca Pazos, M., Berné Valero, J.L., Herráez Boquera, J., " Métodos topográficos". Editorial Paraninfo. ISBN-84-283-2309-7

[7] Chueca Pazos, M., Herráez Boquera, J., Berné Valero, J. "Teoría de errores e instrumentación". Editorial Paraninfo. ISBN 84-283-2308-9

[8] Luceño Vázquez, A., González Ortiz, F.J., "Métodos estadísticos para medir, describir y controlar la variabilidad", Editorial Universidad de Cantabria, 2005, pp.68–73.