APPLICATION OF A VULNERABILITY MODEL FOR BRIDGES OVER STREAM BEDS AGAINST FLOODS IN 100 CASES OF THE SPANISH ROAD NETWORK

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ABSTRACT

The flooding that occurs every year all over the world, together with its terrible consequences, highlights the importance of a methodology to control the state of structures over stream beds. This methodology would allow catastrophes to be anticipated and their effects to be limited, and it would also serve to establish priorities and provide a global view of the structures (a fundamental aspect of bridge management).

This article presents an original methodology that serves to establish the vulnerability of bridges over stream beds against flooding on the basis of field inspections. The methodology was later applied to 100 cases of the Spanish road network managed by the Public Works Ministry.

The methodology establishes the level of vulnerability of the bridges against flooding by means of three descriptors: two for the bed and one for the bridge. These descriptors are derived from a series of parameters and aspects obtained during the supporting field inspection. This field inspection includes all the data regarding the most important factors involved in the bed-bridge interaction during flooding. The three descriptors are finally joined to obtain the Global Bridge Descriptor, which summarises all the information.

1. INTRODUCTION

The existence and application of a methodology to control the state of bridges, which are a key element of road infrastructures because they are essential to cross water ways and link up the whole country, seems necessary in view of the catastrophic consequences that large water floods have on infrastructures [2, 3]. This issue has traditionally been addressed by analysing the undermining situation of specific structures at given times, almost always as a consequence of an exceptional event that placed the structure in danger even of collapse. This method does not allow the effects of catastrophes to be anticipated or limited [4], and it also does not provide a global view of the structures (an essential issue in bridge management).

In recent years, the Universidad Politécnica de Valencia and INES Ingenieros (Torroja Ingeniería also participated during the preliminary stages), with the backing of the Ministerio de Fomento (Public Works Ministry), have developed a methodology to assess the vulnerability of bridges to stream beds in the event of flooding by means of a simple field data acquisition campaign. This methodology has been calibrated and validated by applying it and comparing it in 100 bridges of the Spanish road network, within the framework of the Sistema de Gestión de Puentes (Bridge Management System) that the Ministerio de Fomento uses to manage its roadways.

It is true that the local erosion of the river is one of the greatest challenges that bridges over water ways must face, but it is not the only one. There are other hydraulic problems associated with the bed-bridge interaction during a flooding scenario [6], including those associated with insufficient hydraulic capacity, hydrodynamic actions of the flow on the structure (even impact of dragged objects/materials), general erosion (lateral migration, incision, etc), erosion by contraction and, finally, of course, the undermining of piers and abutments.

All of this highlights the importance of developing a methodology that considers the bed-bridge interaction during a flood as a whole so as to establish the vulnerability of each of the bridges in the road infrastructure network. This will ensure that minor actuations can be carried out to avoid larger problems and also that priorities can be established for those actuations depending on the vulnerability [7].

This article shall present a summary of this original methodology that provides a tool to establish the vulnerability of bridges over stream beds against floods. After this presentation, a set of 100 cases from the Spanish road network with various structural typologies shall be presented, and the results obtained shall be analysed. A preliminary characterization of the bridges of the Spanish road network and of the sample bridges that have been used to develop the proposed methodology shall be performed in the following sections.

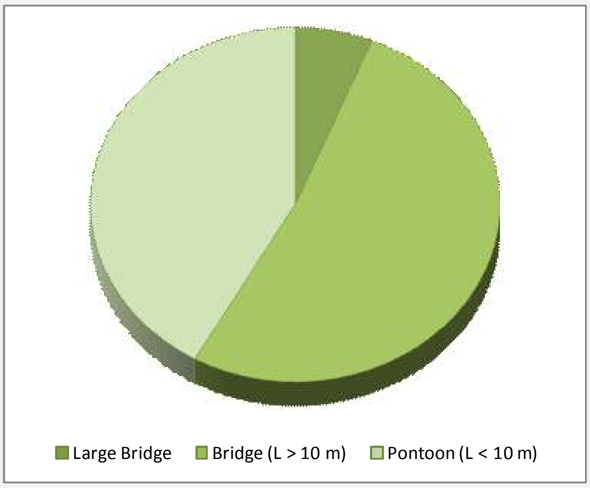
2. CHARACTERISATION OF THE BRIDGES OF THE SPANISH ROAD NETWORK

The purpose of this section is to show that the sample of the inspected bridges (the following section) covers almost the whole spectrum of potential cases and that it allows the possibility of analysing whether the samples are representative not on a statistical level but on a typological level, that is, as regards the relative weight of the various typologies under analysis.

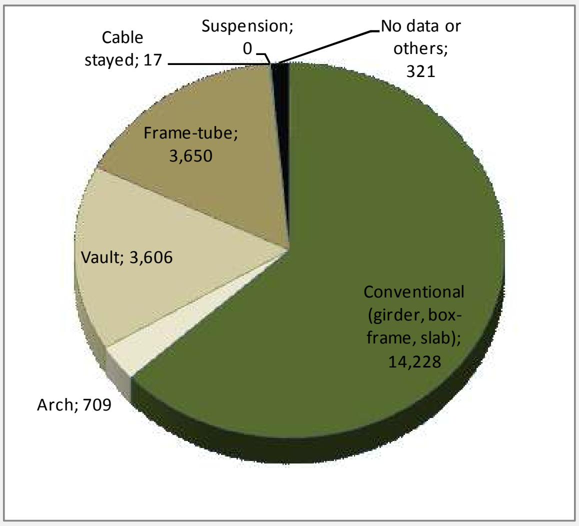
Regarding the evolution of the Spanish road network, official data from the Dirección General de Carreteras (Road Network General Directorate) of the Public Works Ministry show that the high capacity network (motorways and dual carriageways) has doubled in extension in recent years (a growth from 5,400 km in 1992 to almost 10,800 in 2008), whereas the conventional network has remained almost constant. On the other hand, the conventional network has remained constant at around 15,000 km, and has even shown a slight decrease during the aforementioned period. This evolution of the extension of the road network by type of roadway leads us to think or at least to expect (due to the specific weight of the structures of the new high capacity roadways) that there has been an improvement in the overall behaviour of the bridges from the point of view of their vulnerability. This fact can be confirmed, if necessary, with the large-scale application of methodologies such as the one proposed.

The distribution of the bridges of the Spanish road network as regards type of structure (depending on their dimensions or functionalities) and typology (depending on their load-bearing characteristics) is shown in figure 1, below:

Structure Class	TOTAL	%
	22,531	100.00%
Large Bridge	1,386	6.15%
Bridge (L > 10 m)	11,716	52.00%
Pontoon (L < 10 m)	9,429	41.85%



Typology	TOTAL	%
	22,531	100.00%
Conventional (girder, box-frame, slab)	14,228	63.15%
Arch	709	3.15%
Vault	3,606	16.00%
Frame-tube	3,650	16.20%
Cable stayed	17	0.08%
Suspension	0	0.00%
No data or others	321	1.42%



(a) (b)

Figure 1 - Distribution of the bridges of the Spanish road network.
(a) per class of structure; (b) per typology.
Source: Public Works Ministry.

The conventional load-bearing typology includes bridges with girder, box-frame, slab, etc, decks or with other classifications (isostatic, hyperstatic sections, rigid frame or pergola type). The distribution of the conventional bridges in the Spanish road network as per the latter classification is shown in figure 2. According to estimates from the Public Works Ministry, the percentage of bridges over stream beds is of around 40% of the total number of bridges in the Spanish road network. The subset of bridges over river beds thus includes approximately 9000 cases. The new methodology would be aimed at these bridges.

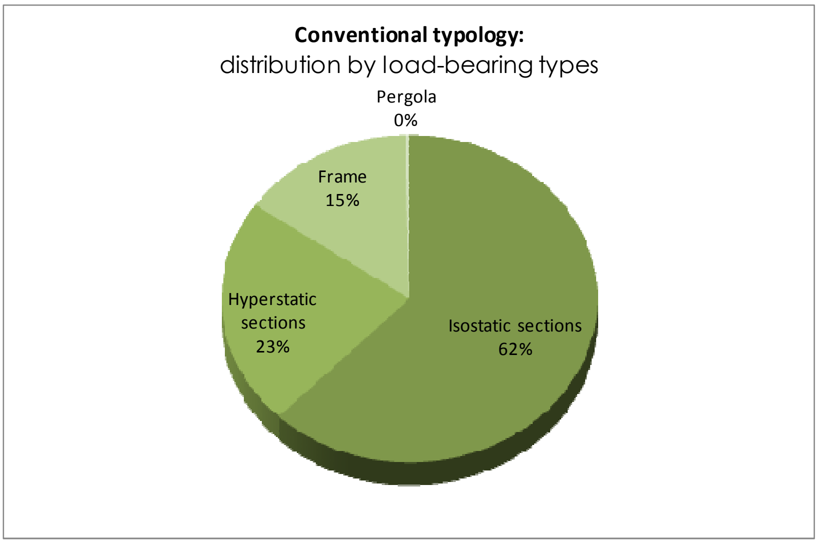


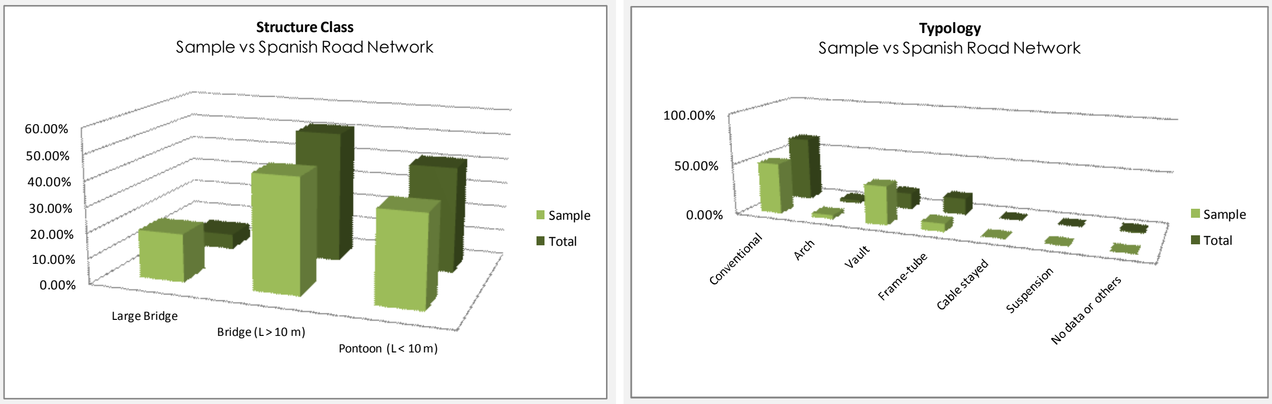
Figure 2 - Typological distribution of the conventional bridges of the Spanish road network.

3. SAMPLE OF BRIDGES INSPECTED. DESCRIPTION AND COMPARATIVE ANALYSIS WITH THE BRIDGES IN THE SPANISH ROAD NETWORK

The scenario of the sample is very different. The distribution by type of structure and typology with respect to the population is shown in figure 3.

Type of structure	Sample	%	TOTAL	%
	100	100.00%	22,531	100.00%
Large Bridge	19	19.00%	1,386	6.15%
Bridge (L > 10 m)	45	45.00%	11,716	52.00%
Pontoon (L < 10 m)	36	36.00%	9,429	41.85%

Typology	Sample	%	TOTAL	%
	100	100.00%	22,531	100.00%
Conventional	50	50.00%	14,228	63.15%
Arch	4	4.00%	709	3.15%
Vault	38	38.00%	3,606	16.00%
Frame-tube	8	8.00%	3,650	16.20%
Cable stayed	0	0.00%	17	0.08%
Suspension	0	0.00%	0	0.00%
No data or others	0	0.00%	321	1.42%



(a) (b)

Figure 3 - Comparative distribution of the bridges in the sample and in the Spanish road network: (a) per type of structure; (b) per structural typology.

Thus, the percentage of 'large structures' or 'large bridges' in the sample is much greater than in the total number of bridges (19 versus 6.2), the percentage of 'pontoons' (span smaller than 10 m) is similar, whereas the percentage of 'bridges' is slightly lower in the sample (45% versus 52%). In this classification, 'large structures' are those that meet any of the following conditions: maximum length of the largest span greater than 40 m, maximum height of the largest pier greater than 25 m or total length greater than 100 m. From the point of view of the load-bearing typology, the most important element is, firstly, the reduction in the relative weight of the conventional bridges in the sample with respect to the total (13% lower), secondly, and importantly, the large increase in the number of vault bridges in the sample with respect to the total (38% versus 16%) and finally the lower specific weight of the typology known as Frame-Tube (8% in the sample versus 16% in total). However, this latter point is easy to explain because bridges of this typology normally have spans smaller than 5 m and the criterion to inspect stream beds is that they should have a span of at least 6 m.

As regards presence or number of structures, the relative weight of smaller typologies is not very significant either in the sample or in total. The typologies set out in the above paragraph represent 96% of the total number of elements in the sample or 95% of the total number of bridges.

Therefore, in this sense it must be noted that the sample considered is not only important because of the number of stream bed bridges analysed, but also because of how representative the typologies of the bridges are. However, it is also important to stress the importance of vault bridges in the sample, because it makes it significantly harder to evaluate the results obtained in the sample as a set of data, that is, from a global point of view. This should therefore eliminate any temptation to extrapolate the conclusions obtained in the sample to all the bridges.

4. NEW METHODOLOGY TO EVALUATE THE VULNERABILITY OF BRIDGES OVER STREAM BEDS AGAINST FLOODING. PRESENTATION AND SUMMARY

The proposed methodology is based on the analysis of a large number of inspected bridges and on the professional experience in the fields of both inspection (even forensic inspections on collapsed bridges) and development of classical studies and bridge repair projects. The methodology relies on the main factors involved in the bed-bridge interaction during a flood scenario [5]. There is no need to perform hydrological-hydraulic or structural simulations (this is the classical approach and its implementation within a bridge management system is extremely expensive) and the descriptors or vulnerability indicators are obtained during a field data acquisition campaign. This information is later used at the office to reach a single final numerical value. The data collected during the field inspection are only those that are strictly necessary.

The proposed methodology establishes the level of vulnerability of the bridges against flooding by means of three descriptors that must be used jointly: two for the bed (Upstream Stream Bed Descriptor and Downstream Stream Bed Descriptor) and one for the bridge (Bridge Descriptor). These descriptors are developed from a series of parameters and aspects obtained during the supporting field inspection. This inspection serves to systematically and objectively compile all the data needed to consider the factors that have an influence on the bed-bridge interaction during a flooding scenario, those that constitute the basis of the subsequent calculation process. These factors are of a geomorphological, hydraulic-sedimentological and structural nature. Geomorphological factors refer basically to properties of the beds and their banks. Their characteristics and effects are important for the analysis of bridge stability issues associated to the interaction with the bed during flooding scenarios. Hydraulic-sedimentological factors are significant to evaluate the vulnerability of the bridge substructural elements to the stream bed. The type of interaction between the bridge and the stream bed and, thus, the effects derived from it, depends on these factors to a large extent. They serve to evaluate issues associated to lack of hydraulic capacity, river stability in areas close to the structure, erosion due to contraction and undermining and hydrodynamic action of the stream on the structure itself. Finally, structural factors are related to the load-bearing characteristics, although sometimes also the soundness characteristics, mainly for the elements of the substructure and its foundations, including their protection measures.

A new inspection [8], the Stream Bed Inspection, has thus been designed. It is established as the on-site inspection of bridges on stream beds that is performed from the point of view of the flood-bed-structure interaction and that takes into consideration all the intervening factors (geomorphological, hydraulic-sedimentological and structural) that are essential to evaluate the vulnerability of the bridge against floods. This inspection has been included within the framework of the main inspections by designing Bridge Stream Bed Inspection Sheets and the corresponding Bridge Stream Bed Inspection Manual. The inspection sheets include all the information needed for the subsequent automatic application of the original evaluation methodology proposed.

The bed descriptors are obtained from a series of global codes that serve to evaluate the stream beds. Thus the Upstream Stream Bed Descriptor is formed by six figures (four integers and two decimal points) or digits of the stream bed descriptor (DSBD) that reflect the state of the stream bed as indicated in the evaluation performed by the inspector for all the aspects in table 1, below (the corresponding parameters are included in the inspection sheet).

Table 1 - Aspects considered in the Upstream Stream Bed Descriptor.

	ASPECTS IN THE UPSTREAM STREAM BED DESCRIPTOR
1_	Contraction index
2_	Natural or artificial obstruction index
3_	Location, type and status of the protection measures
4_	Undermining basins in the bed
5_	Type of stream bed
6_	Potential for blocking with dragged objects/materials

As regards the Downstream Stream Bed Descriptor, the calculation procedure is similar, but with the aspects detailed in table 2. The number obtained shall have five figures (three integers and two decimal points) instead of six.

Table 2 - Aspects considered in the Downstream Stream Bed Descriptor.

	ASPECTS IN THE DOWNSTREAM STREAM BED DESCRIPTOR
1_	Natural or artificial obstruction index
2_	Location, type and status of the protection measures
3_	Undermining basins in the bed
4_	Type of stream bed
5_	Index of blocking with dragged objects/materials in the stream bed

As regards the Bridge Descriptor (BD), the code that defines it indicates the vulnerability of the bridge, both in its current state and against potential unfavourable effects of river processes (hydraulic-sedimentological) such as undermining, sedimentation or silting, migration of the bed away from the bridge, hydrodynamic forces, loading due to hydraulic pressure, etc. This descriptor is evaluated by means of codes (table 3) and cases associated to these codes, which represent specific combinations of parameters and/or aspects established for the bridge substructural units. These combinations represent equivalent status conditions or equivalent vulnerability scenarios. The value of this descriptor is within a range of 3 to 8, and each value of the range is subject to a subset of potential cases. This type of evaluation or estimate of the descriptor is used to obtain final indicators that can be compared to those used in other countries [1].

Table 3 – Bridge Descriptor. Range of codes.

CODE	CONDITION. General Description of the Main Aspects.
N	**Not Applicable. Indicated for bridges not located over stream beds.**
9	**Excellent**. Assigned only by expert personnel of the technical office. Bridges with high clearances where all the substructural units are over the flood stream, with a 500-year return period.
8	**Very good**. For bridges that are classified as transversal drains or bridges with foundations for the substructural units placed on competent rock.
7	**Good**. The substructural units are adequately protected by corrective actions or these corrective actions are not necessary.
6	**Satisfactory**. The substructural units are in contact with the bed material, where there are many stones and pebbles and there is little or no indication of instability. Minor damage.
5	**Acceptable**. The substructural units are in contact with the bed material, where there are many stones and pebbles and the bed displays some instability. Damage and some undermining.
4	**Poor**. The substructural units are in contact with the bed material, which is mainly made up of degradable and fine material. Loss of material, important undermining. Essential elements are affected.
3	**Bad**. The substructural units are in a critical condition regarding undermining and/or obstruction, to such an extent that the bridge structure is threatened. Danger of total collapse.
2	**Critical**. Important damage in the main elements (undermining or obstruction that could make these elements collapse, major lack of hydraulic capacity). The bridge is CLOSED.
1	**Imminent failure**. Important damage, loss of material, extensive undermining that affects the structural stability. Emergency actuation. Real threat to the bridge structure. IMMEDIATE ACTION IS REQUIRED.
0	**Failure**. Code 0 indicates that the bridge has collapsed. Rebuilding actions.
666	**Not enough information**. Expert evaluation needed.

The assignment of a code to a substructural unit is done after an on-site (and/or office) inspection to obtain the necessary data for at least the parameters or aspects indicated in table 4, below:

Table 4 – Parameters or aspects to be inspected for the bridge substructural unit code

	PARAMETERS OR ASPECTS TO BE INSPECTED TO ESTABLISH THE BRIDGE STRUCTURAL UNIT CODE
1_	**Type of Structural unit** _[type and *material of the pier*, and *type and material of the abutment*]
2_	**State of the Element**_[pier and/or abutment only in the case of serious damage, affecting its load bearing state, in low codes]
3_	**Striking angle to the substructural unit**_[striking angle for piers and abutments]
4_	**Type of foundation of the substructural unit** _[surface, semi-deep or deep]
5_	Type of **material of the bed** near the substructural unit (close to it and next to it) – the ideal scenario would be knowing the type of **foundation material**-
6_	Undermining/silting status
7_	**Type and preservation status** of the substructural unit **protection measures** (protective-corrective) (if any)
8_	Evidence of movement of the substructural unit_[relative movement of the substructural unit with respect to the bridge deck].

Priority criteria shall be applied if more than one code applies to the situation of a substructural unit so that the most unfavourable case is used. Each substructural unit shall be qualified with a single code although several cases may apply to a single unit. If the collected data are insufficient or the local boundary conditions do not allow the substructural unit code to be calculated, code 666 shall be applied. This situation means that a further special inspection and/or expert intervention shall be needed. The substructural unit code with the highest priority shall also be used in the case of the BD (figure 4). This priority corresponds to the lowest number of the code range. In addition, it will also be necessary to calculate (if applicable) the global obstruction index for this descriptor that represents the status of the structure. This index is calculated 'under the bridge' and is the sum of the natural and/or artificial (bars, stream bed invasions, buildings, consolidated spills, etc) obstruction indexes and the blocking with dragged objects/materials in the stream bed.

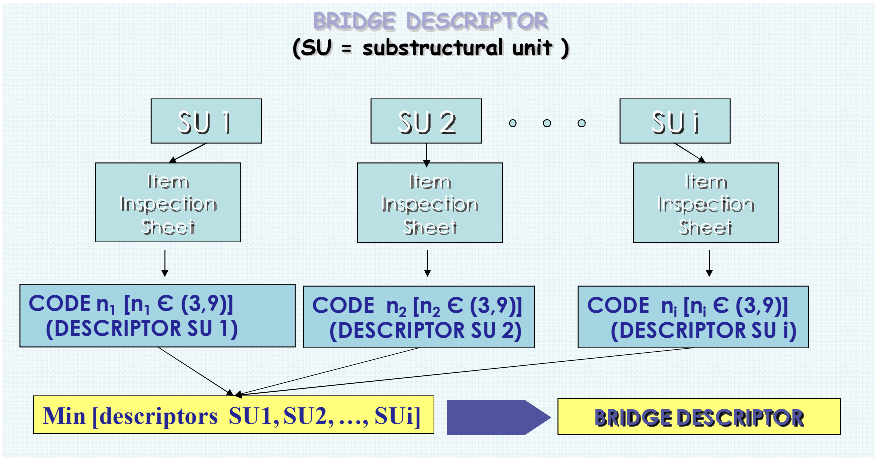


Figure 4 - Final quantification of the Bridge Descriptor.

The estimate of the BD is obtained by establishing the total and complete list of physically possible cases considering the specific combinations of parameter values and/or aspects of the substructural units, the stream bed and their status in the vicinity, as well as the limitations (bars, blocks and accumulations) that lead to one global obstruction index or another. This breakdown of cases (specific combinations or groups of aspects related to the vulnerability of the bridge against floods) is later added into codes depending on their condition (see table 3, above).

The set of basic descriptors considered is shown in figure 5, below:

Figure 5 – Basic vulnerability descriptors used.

Finally, the first two descriptors are combined to obtain the Stream Bed Descriptor (SBD), and this common stream bed indicator is merged with the Bridge Descriptor (BD) to obtain a single value to compare the vulnerability status of bridges. This single descriptor is known as Global Bridge Descriptor (GBD) and it concentrates and summarises all the information. In the case of bridges in operation, this single value ranges between 3 (serious deficiencies) and 8 (very good condition). This serves to optimise the treatment of data within a Bridge Management System (for instance, the Spanish road network). A chart, known as the GDB chart (figure 6), has been developed to make it easier to obtain this value and to handle the large volume of results that are generated when a wide range of cases are analysed. The GBD can be obtained simply by placing a case on the chart, by its coordinates [SBD, BD] and noting the vulnerability region in it is located. Besides, this chart is an important management tool because it not only displays the value of the current GDB, but it also indicates the optimum path (from the point of view of the actuations needed, of stream bed or structural engineering), by moving to other regions, towards its improvement (increase in value) and the reduction in bridge vulnerability.

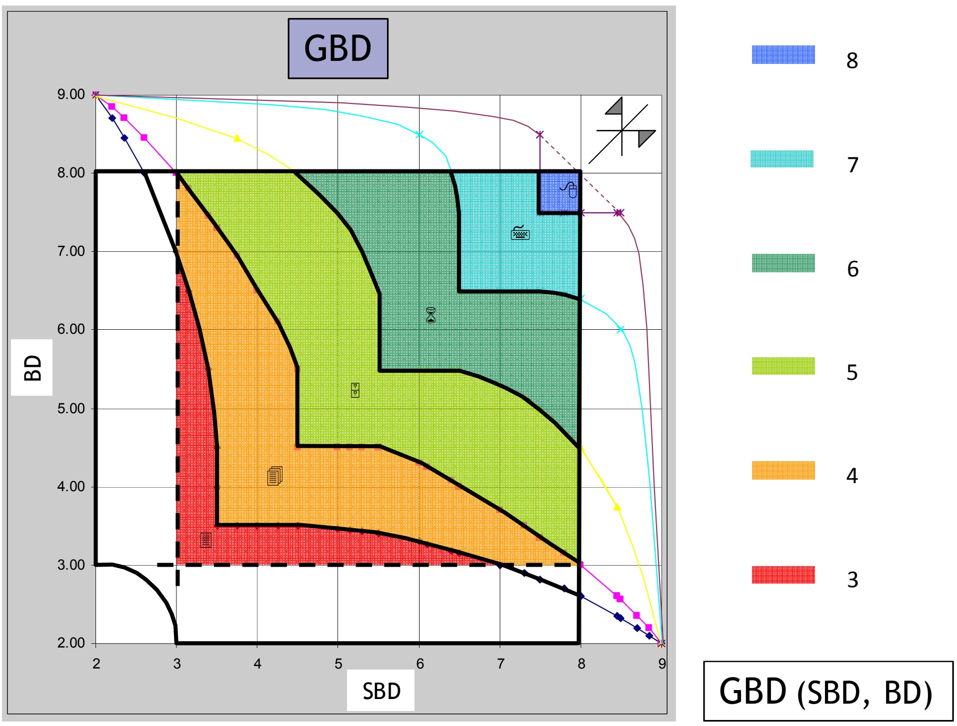


Figure 6 – Global Bridge Descriptor [GBD] chart

Once the descriptors in a certain set of real cases have been obtained and it is necessary, for any reason (e.g: budget constraints), to select the 'n' worst cases that would require a more immediate or urgent actuation, the methodology itself can arrange them, even within each vulnerability region of the proposed chart. Thus, within level 3, which corresponds to the cases in the worst condition and thus with the greatest vulnerability (which is considered equal for all the cases within it), the actuation priority required is not the same for all cases. Figure 7 shows the general recommendation for the establishment of priorities within level 3 of the chart (the one that indicates the worst state). This zigzag path within the section is the general recommendation considering no bridge has been moved to code 2 (critical condition; GBD=2) or even code 1 (imminent failure; GBD=1) due to the seriousness of its situation, since this would make these bridges a priority, including removing them from service and acting immediately.

The same scenario applies for the rest of the areas in the chart, where the most pressing cases also cross the chart diagonally and are therefore found on the apexes of each region. The actuation priority path would also zigzag from right to left, as shown in figure 7 for area 3 of the chart.

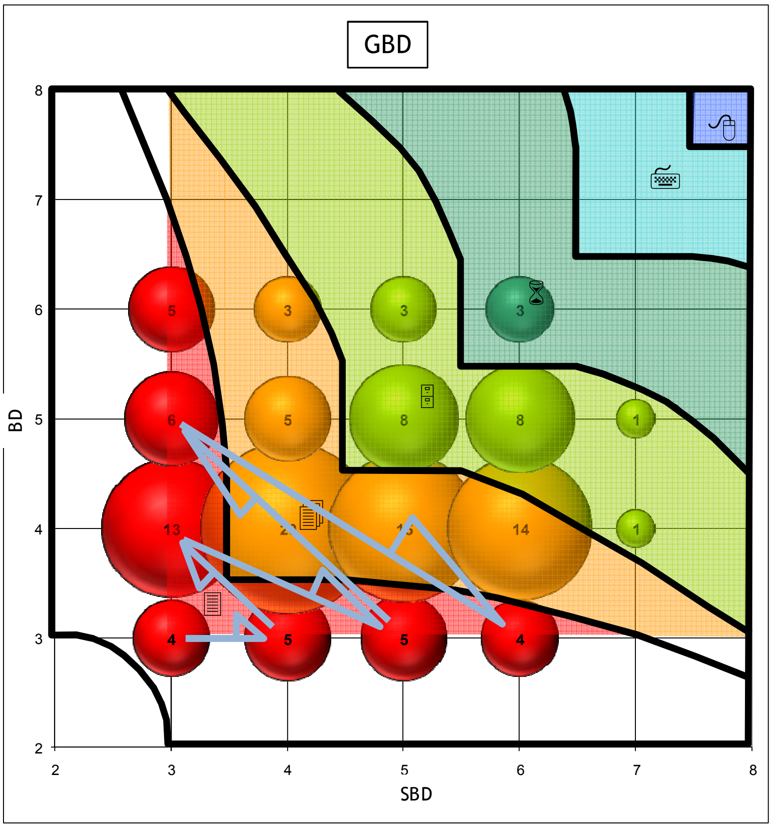


Figure 7 – Establishment of actuation priorities within the areas of the GBD chart. Case for level 3.

After its development, the original methodology proposed was compared with a series of real cases that had either been studied with a classical method or had collapsed, and the results were highly satisfactory. This finally allowed the standardisation process proposed for the three descriptors to be validated, and thus the GBD to be established as the only final indicator.

5. APPLICATION OF THE METHODOLOGY AND ANALYSIS OF RESULTS.

A spreadsheet was developed to automatically apply the proposed methodology. This spreadsheet processes the bridge inspection information, detects formal errors and inconsistencies and then performs the necessary calculations (dimensional ratios, contraction indexes, etc) to obtain each of the DSBD, and therefore all of the stream bed descriptors, and to check that a given real case under study belongs in a specific equivalent vulnerability case and therefore in one code or another. The Bridge Descriptor is thus obtained.

The spreadsheet includes a header with general information on the case under study (in the same way as the inspection sheets) and a summary table with the values obtained for each of the three basic descriptors (Figure 8). The structure of the sheet is then divided into four parts: input data (the data from the Main Stream Bed Inspection Sheet), Upstream Stream Bed Formulation to calculate this descriptor, Downstream Stream Bed

Formulation to calculate this descriptor and Bridge Formulation to obtain the Bridge Descriptor.

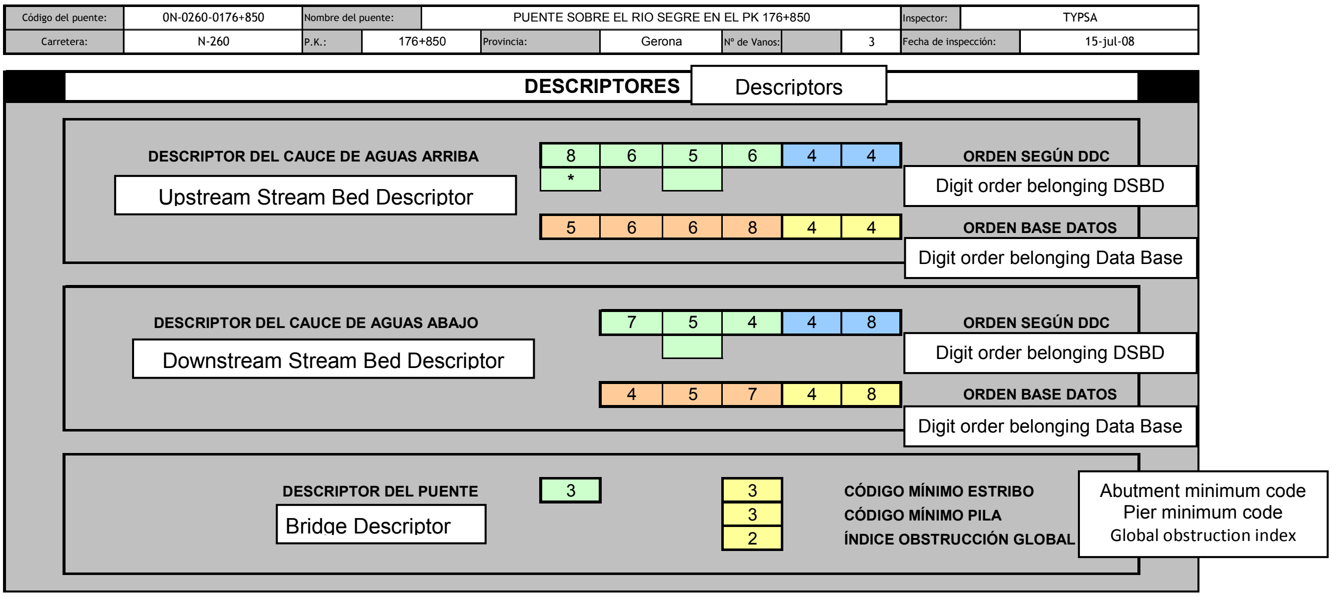


Figure 8 – Spreadsheet (ORIGINAL) to calculate the vulnerability descriptors. General information and summary table.

The methodology applied has managed to determine the three basic descriptors (and thus the vulnerability of the bridge against flooding) in all 100 cases analysed. In some cases all the information, or at least all the information necessary, was available, and in others the 'management decision' was taken (this happened in 22% of the cases, where surface foundations were assigned because the inspector indicated in the sheet that the foundations were 'not defined' or 'not observed').

Once all the inspection information was processed and the values of the three basic descriptors had been obtained, the Global Bridge Descriptor as a single indicator was calculated. In each case, the final result is the GBD and its two coordinates in the Global Descriptor chart, that is, the Stream Bed Descriptor (SBD), which assesses the stream bed in the area affecting the bridge, both upstream and downstream, and the Bridge Descriptor (BD). The general analysis of the results obtained is thus shown in figure 9. Figure 10 shows the behaviour of the Global Bridge Descriptor.

The Stream Bed Code in the sample under analysis is basically distributed in the range between 3 and 6 (50% of the cases analysed are spread in each half of this interval, although the smaller percentage is for the most unfavourable code (18%)). 30% of the cases are in poor condition, whereas 26% are acceptable and the remaining 24% are satisfactory. The behaviour of the Bridge Descriptor points clearly towards the values that indicate a worse state and the greatest concentration is found in BD value 4 (47% of the cases with results). 13% of the cases are in bad condition and 40% of the cases are either acceptable or satisfactory. However, it is important to note the influence of the decision (due to lack of information) of assigning surface foundations to a certain structure. This influence of the so-called 'management decision' on the BD is also reflected on the final value of the GBD. This issue shall be analysed in further detail later.

Stream Bed Descriptor			
SBD	CONDITION	N	%
3	Bad	18	18.0%
4	Poor	30	30.0%
5	Acceptable	26	26.0%
6	Satisfactory	24	24.0%
7	Good	2	2.0%
8	Very Good	0	0.0%
	TOTAL	100	100.0%

Bridge Descriptor			
BD	CONDITION	N	%
3	Bad	13	13.0%
4	Poor	47	47.0%
5	Acceptable	27	27.0%
6	Satisfactory	13	13.0%
7	Good	0	0.0%
8	Very Good	0	0.0%
	TOTAL	100	100.0%

Figure 9 – Sample of inspected cases. SBD and BD. Analysis of results.

Global Bridge Descriptor			
DGP	CONDITION	N	%
3	Bad	29	29.0%
4	Poor	47	47.0%
5	Acceptable	21	21.0%
6	Satisfactory	3	3.0%
7	Good	0	0.0%
8	Very Good	0	0.0%
	TOTAL	100	100.0%

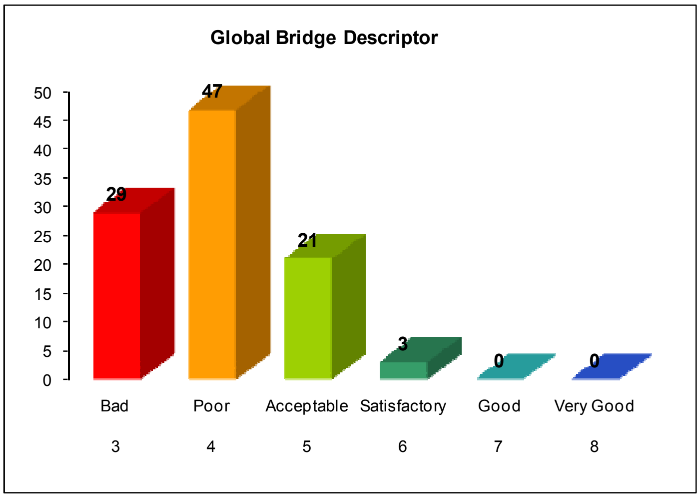


Figure 10 - Sample of inspected cases. GBD. Analysis of results.

This behaviour of the BD, together with the fact that there are only two cases with a value of 3 for the two main descriptors (SBD and BD) and that both carry the same relative weight, gives the GBD a very similar formal distribution, but with an even greater tendency towards the lower values of the condition spectrum. In this case, 29% of the cases are in a bad condition, whereas the number of cases in a poor condition remains the same. 24% of the cases analysed is in an acceptable or satisfactory condition.

Figure 11 shows the cases covered by the sample with respect to the total number of possible values for the GBD. The sample can be seen to include real cases that cover a significant portion of the range of possibilities. The size of the spheres in figure 12 indicates the exact number of bridges in the sample with a certain position within each of the areas of the chart (that are colour-coded and correspond to different values of the GBD).

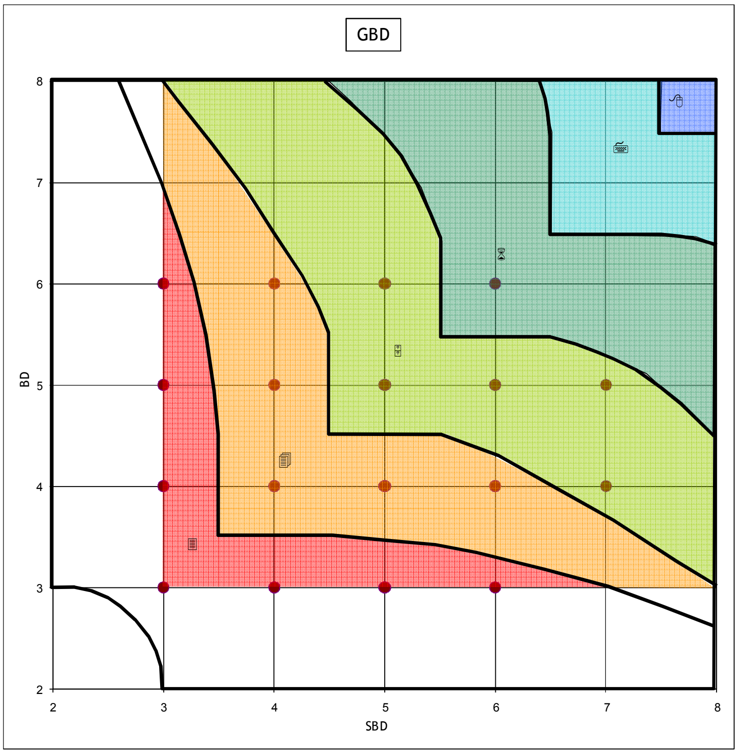


Figure 11 – Representation of results on the GBD chart. Existing cases in the sample.

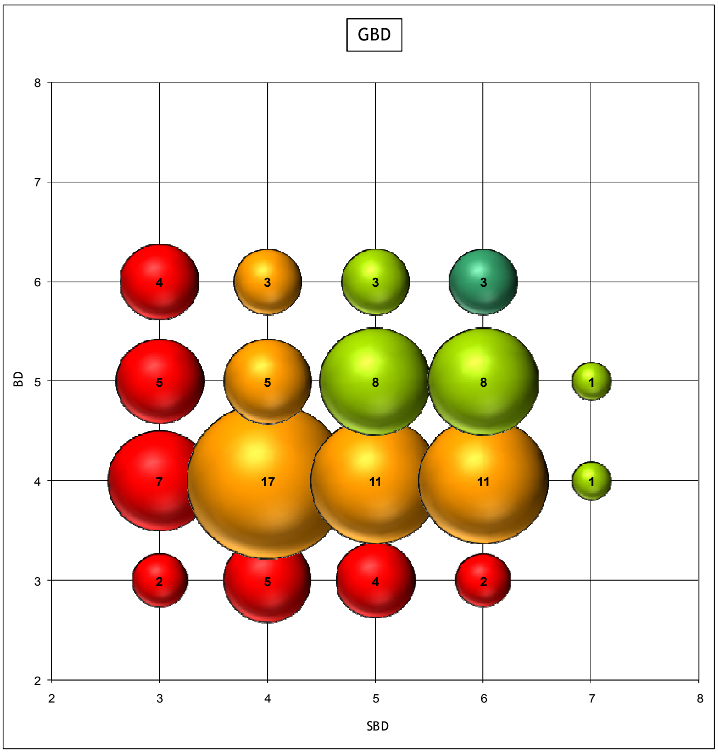


Figure 12 – Number of cases of the sample analysed in each section of the GBD chart.

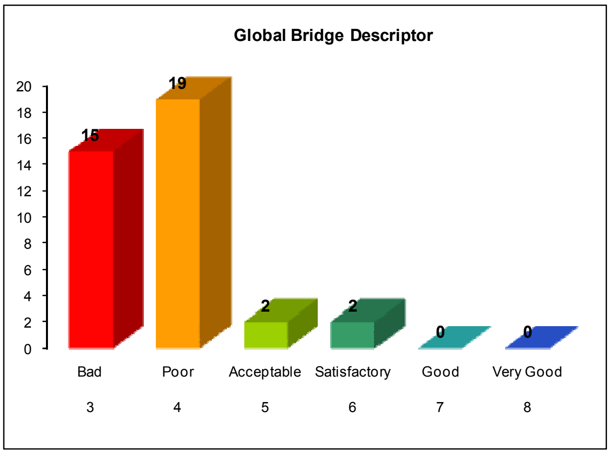
The breakdown considered for the analysis by typologies is consistent with the classification used, but it has the highest degree of breakdown. It is divided into the following: isostatic section, hyperstatic section, vault, arch and culvert. No other typologies have been considered because they are not found in the sample. The analysis done for the GBD essentially leads to the following conclusions: isostatic bridges have a similar behaviour to the whole sample while vault bridges display the worst behaviour. The lack of cases of the remaining typologies means that, in our opinion, no conclusions can be drawn.

The case of vault bridges needs to be analysed independently (figure 13). These structures are more robust and monolithic but also more fragile, and in general display a worse behaviour than the rest. They are older, their foundations and materials are in a worse condition and they display higher contraction indexes and levels of obstruction during flooding, so their final vulnerability descriptor values are lower and thus worse than the rest of the cases. They are distributed basically throughout the values that indicate a worse condition: 40% of the cases are in a bad state and 50% are in a poor state, adding up to 90% of the total number of cases of these types. The importance of the vault bridges in the sample (see section 3) and their differential behaviour compared with the others mean that it is not actually possible to directly extrapolate the results of the cases analysed to all the bridges.

Finally, to conclude the analysis, the influence of the foundations on the final level of bridge vulnerability against flooding is evaluated within the proposed methodology. One of the following options needs to be selected in the inspection sheets: 1: surface; 2: semi-deep; 3: deep; 4: not defined; and #: not observed. 'Not defined' shall be used whenever there are any doubts and 'not observed' shall be used whenever the foundation cannot be seen or the project information is not available.

Vault bridges. Global Bridge Descriptor

DGP	CONDITION	N	%
3	Bad	15	39.5%
4	Poor	19	50.0%
5	Acceptable	2	5.3%
6	Satisfactory	2	5.3%
7	Good	0	0.0%
8	Very Good	0	0.0%
	TOTAL	38	100.0%



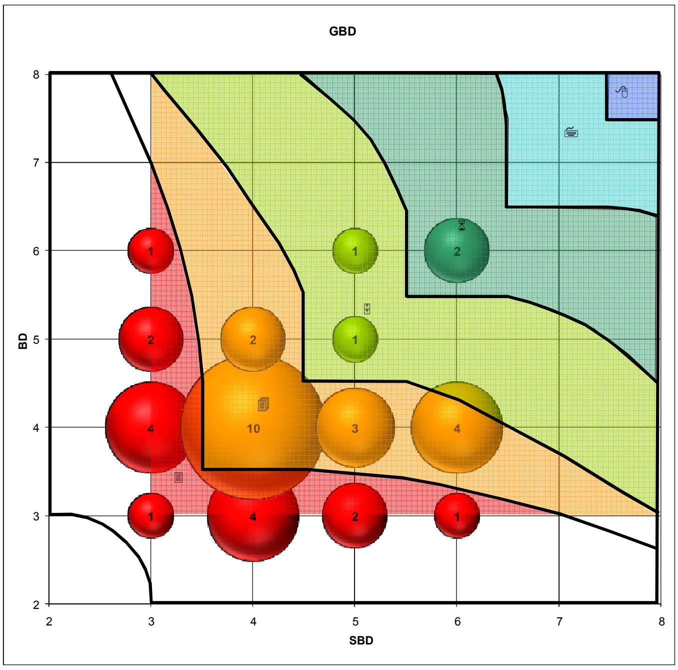
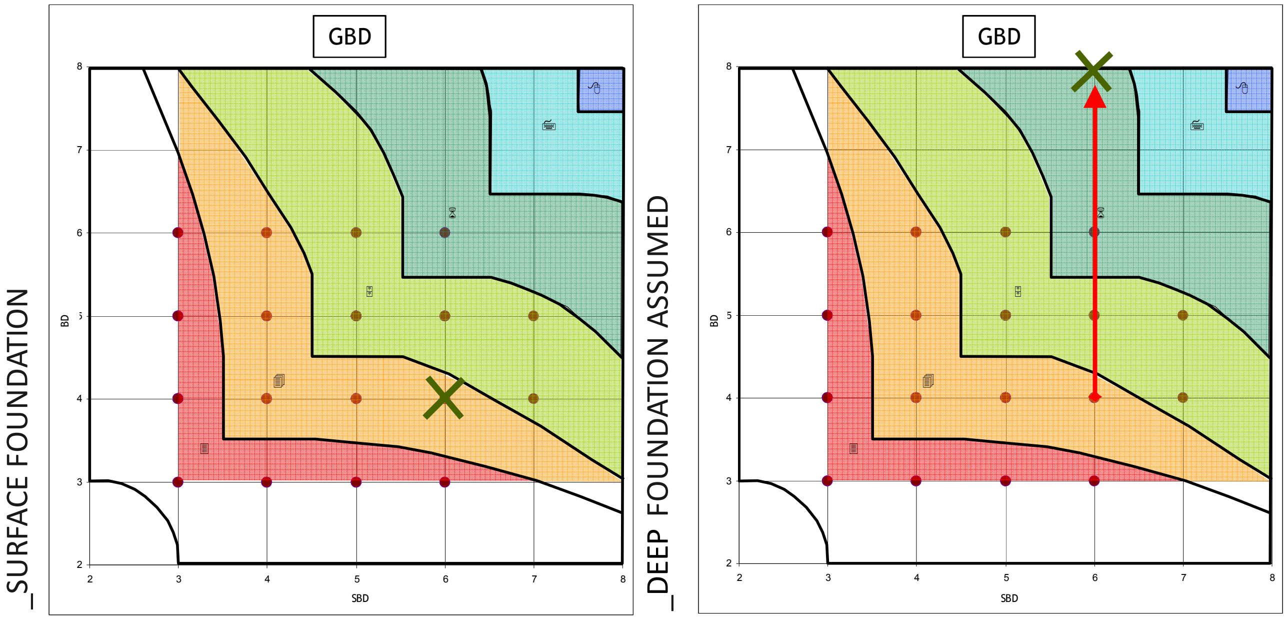


Figure 13 – Vault bridges. Distribution and representation of results in the GBD chart.

Surface foundations mean that the code for the substructural unit (abutment, pier) has a low value, so, in practice, the Bridge Descriptor rarely exceeds level 4 (poor condition), and semi-deep or deep foundations are not a serious limitation for an element of the substructure. This means that, if no data are available and the manager therefore decides to assign a type of surface foundation to a specific substructural unit as a safety criterion, the condition of the structure based on the BD is reduced, and this is often reflected directly on the GBD as a final indicator (figure 14).



Bridge Code	Typology	Foundation	SBD	BD	GBD	BD'	GBD'
PT069	Vault bridge	surface foundation	6	4	**4**	8	**6**

BD' = Bridge Descriptor with deep foundation

GBD' = Global Bridge Descriptor with deep foundation

Figure 14 – Influence of the foundations on the evaluation of bridge vulnerability against flooding.

This has been found in 22 out of the 100 cases of the sample of bridges in the Spanish road network. In most cases, considering surface foundations has caused a reduction in the BD, and in 10 of these cases there has also been a reduction in the final value of the GBD with respect to the hypothetical value for deep foundations. In the most extreme case (bridge 069), the GBD would change from 6 to 4 with surface foundations as a result of the change in BD from 8 to 4. This fact is important because the condition of a given bridge is considered to be represented by a GBD=4 (poor condition) when it could really be a satisfactory case (GBD=6).

6. CONCLUSIONS

The proposed methodology is based on specifically-designed field inspections (stream bed inspection). In this sense it is essential to stress the importance of good training of inspectors to ensure reliable and accurate data acquisition. This training involves a specific course prior to the field data acquisition campaign and one or several days to submit questions and follow up on the results. This inspection shall be objective, systematic and complete, and it shall also be standardised (inspection sheets). It is complete because it takes into account the interaction between the stream bed and the bridge during flooding on a global scale (general erosion, contraction and local erosion, load increases, hydraulic capacity issues, problems associated with the transport capability of the stream bed during flooding and even with the type of stream bed, etc). Therefore, a minimum inspection time is needed to ensure the quality of the information gathered is enough. On average, between 1 and 1.50 hours are needed for the bridges of the Spanish road network managed by the Public Works Ministry.

The proposed methodology is certainly specific because it assigns a level of vulnerability against flooding to the inspected bridges and classifies them according to that vulnerability. It does not lose the physical meaning of the parameters and aspects that gather the main intervening factors to produce the classification and ultimately allows the bridges in a worse condition to be pinpointed so that they are given priority and the necessary actuations are applied (as regards the aim of the measures to be applied on the bridges). This serves to optimise the available and always limited resources. Obviously the ultimate definition of these actuations must be studied in detail.

The methodology makes it possible to know whether the vulnerability is caused by an undermining process (visible) or by phenomena that are not directly noticeable (contraction of the width of the stream bed, potential obstructions, etc) that would go unnoticed during a conventional visual inspection and that point towards a hazardous situation with the proposed methodology.

REFERENCES

1. Cinotto, Peter J. and White, Kirk E. (2000). Procedures for Scour Assessments at Bridges in Pennsylvania. Open-File Report 00-64. U.S. Geological Survey. U.S. Department of the Interior.
2. Fernández Bono, J.F. y Vallés Morán, F.J. (2001). Análisis de los Procesos de Dinámica Fluvial Provocados por la Avenida de octubre de 2000 en la Rambla Cervera (Castellón) y su Influencia en la Inestabilidad y Colapso de los Puentes que salvan la Rambla en las Carreteras CV-132, CV-10 y CV-135. Grupo de Ingeniería Fluvial. IIAMA. Universidad Politécnica de Valencia. España.
3. Fernández Bono, J.F. (2003). El Caso de los Cauces del Torrent Mal y la Riera Magarola en Esparreguera (Barcelona). Curso de Especialización Ingeniería Fluvial. Fundació Politècnica de Catalunya. Universitat Politècnica de Catalunya. España.
4. Fernández Bono, J.F. y Vallés Morán, F.J. (2004). Cuantificación de la vulnerabilidad de puentes sobre cauces frente a avenidas. Proceso metodológico. Casos reales. Memorias XII Convención Científica Internacional de Ingeniería y Arquitectura. CUJAE. Ministerio de Educación Superior. Cuba.
5. Lagasse, P.F., Schall, J.D., and Richardson E.V. (2001). Stream Stability at Highway Structures. HEC 20. Hydraulic Engineering Circular No. 20; Third Edition. Report No. FHWA NHI 01-002. Federal Highway Administration. U.S. Department of transportation. Washington, D.C.
6. Vallés Morán, F.J. (2002). Interacción Avenida-Cauce-Estructuras I.- Interacción con Obras No Hidráulicas: Puentes. II Jornadas de Ingeniería Fluvial. Colegio de Ingenieros de Caminos, Canales y Puertos. Valencia. España.
7. Vallés Morán, F.J. y Fernández Bono, J.F. (2006). Metodología Sistemática para la Cuantificación de la Vulnerabilidad de Puentes sobre Cauces frente a Avenidas. Aplicación a Casos Reales. XXII Congreso Latinoamericano de Hidráulica Ciudad Guayana, Venezuela, IAHR.
8. Vallés Morán, F.J., Arias Hofman, G. y Fernández Bono, J.F. (2009). Manual de Inspección Principal de Cauces. Obtención de datos para la evaluación de la vulnerabilidad de un puente frente a avenidas. Universidad Politécnica de Valencia e INES ingenieros consultores. España.