Benefits of the instrumentation, monitoring and control systems (IMC) of bridges in Colombia, from an economic point of view through a case study

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Abstract. An instrumentation, monitoring and control (IMC) system is the result of the application of different branches of engineering such as electrical, systems and telecommunications, applied to solve a problem in civil engineering, and achieving a radical innovation in the construction and maintenance of bridges. These different branches come together to carry out activities such as the development of measurement instruments, applications for the storage and analysis of data, and the transmission thereof. This article presents the state of art about road infrastructure controls in Colombia, particularly on bridges. It summarizes some important cases of collapse with their main causes, establishing as an effective solution IMC of the bridges throughout the structures’ life cycle, showing the benefits associated with the initiation of the system. In addition, an economic analysis of the installation of an IMC system is presented through a case study of one bridge located in Colombia, which has enabled us to identify and find relevant information related to those responsible for the project, the required instrumentation and the investment percentages regarding this particular type of project. The text consists of seven sections, which address the problems, instrumentation, software and personnel requirements for this type of project in Colombia, and finally to examine the associated costs.

1. Introduction
In the last few years, there has been a regular increase in the amount of problems related to the stability of the bridge structures in different countries [1]. Regardless of whether the structure is under construction or is in operation, the need to monitor structures throughout their life cycle has been demonstrated [2]. In a large number of cases, the stability of the structure is so affected that its collapse is inevitable. The following table shows several cases of bridge collapse (See Table 1).

It is necessary to mention that the causes of collapse of bridges vary, depending on whether the structure is in use or not. However, it is common to mention at the beginning of the investigations the following factors for bridges that are under construction: problems in design, foundations, material quality and geology [3]. In the case of bridges in operation: aging, corroded concrete, and lack of investment in maintenance [4] [5] [6]. Other cases may be due to the particular use of the structure [7]. Generally, stability problems generate various cost overruns in projects that can be avoided, within the different repercussions we have: questions in engineering, professionals [8], companies [3], public entities [9] and in general to the state of intervention within the project. On the other hand, economic
costs are generated for projects [10], insurers and reinsurers [11] [12] [13], mobility inconveniences [14] [15], environmental impact [16] and people injured or deceased [1] [17] [18].

Table 1. Cases of bridge collapse.

| Bridge | Date       | Country |
|--------|------------|---------|
| Morandi| 08 - 14 - 2018 | Italy  |
| Cancura| 06 - 23 - 2018 | Chile  |
| Chirajara| 01 - 15 - 2018 | Colombia |
| Charte | 08 - 22 - 2016 | Colombia |
| Calcutta| 03 - 31 - 2016 | India  |
| Chalma | 06 - 25 - 2014 | Mexico  |

The alternative to reduce and mitigate the problems associated with stability of bridge structures is a bridge instrumentation, monitoring and control system, consisting of an instrumentation system, an information analysis and management system, and an alarm system. The IMC system is made up of computers that allow data acquisition, which will later be analyzed and stored, establishing alerts that generate alarms about the behavior of the structure, all in order to avoid its collapse and, therefore, avoid or mitigate the aforementioned repercussions [19]. Some researchers have been developing associated technology that has been collected in the literature [20].

After the collapse of the Chirajara bridge on January 15, 2018, the controls on structures under construction were strengthened, especially in this type of megaproject. This generated in the initial contract of the case study an addition for the instrumentation, monitoring and control of the bridge, and in turn, the personnel for the execution of the different activities related to the IMC system.

It is important to indicate that in Colombia there is no regulation, state directive, or technical requirement that requires systematic inspection and control of a structure through IMC systems during the life cycle of the bridge.

2. Who exercises control in Colombia
This section is divided into two parts: the first section presents the controls exercised by the main parties involved in the supervision of bridges during their life cycle.

2.1. Those who exercise control
In this order of ideas, two possible cases are described, classified depending on whether the road over which the bridge is located is under the charge of INVIAS, or it is part of a road concession. The following table identifies those involved in the first case.

2.1.1. Road under the charge of INVIAS. INVIAS, as a state authority, formulates and performs the selection process for the building of the structure of a bridge and then opens a selection process designating a contractor and auditor for the execution of the contract. Once the construction is finished, they deliver the work to INVIAS to carry out its administration and maintenance.

2.1.2. Concessioned road. On concessioned roads, depending on the terms agreed to in the contract, after delivery to INVIAS (1.1.1 Road under the charge of INVIAS), the road or bridge is delivered to ANI, which in turn delivers it to the Road Concession in charge of administration and maintenance until its final delivery to INVIAS after the end of the concession contract.
Table 2. Those involved in supervision in Colombia.

| Involved                    | Function according to the stage                                                                 |
|-----------------------------|--------------------------------------------------------------------------------------------------|
| National Institute of roads - INVIAS | Contracting authority of the construction and auditing contractor, and state supervisor of the contract |
| Building Contractor         | Constructor and responsible during the validity of policies of compliance, quality, extracontractual civil liability and stability of work. |
| Auditing                    | Supervisor and responsible by default.                                                            |
| National Agency of Infrastructure - ANI | State authority that receives the work from INVIAS and delivers them road concessions.             |
| Road Concession             | Private company or semi-public association, which performs the maintenance and operation of a road during certain times. |

2.2. Controls performed
Depending on the stage of the life cycle, bridges in Colombia are under the supervision of different stakeholders. In the next paragraphs, we will describe the following stages:

2.2.1. Building contractor. The building contractor performs a basic instrumentation during the construction of the bridge, in order to verify its behavior.

2.2.2. INVIAS. The Bridge Administration System of Colombia (SIPUCOL), assigned to INVIAS, is in charge of the bridges department of the national road network. Currently, it monitors active bridges through visual inspections of the structural elements. This is done based on the professional criterion linked to INVIAS which assigns a quantitative and qualitative grade depending on the current state of the bridge structure. A report is then delivered to contract the necessary activities.

2.2.3. Road concession. Depending on the terms agreed to in the road concession contract, they can be charged with inspections, maintenance and/or adaptation of the infrastructure in their respective road corridors. It is worth mentioning that some road concessions already have structures in place with IMC systems.

3. Overview about controls in the region
In other countries, such as Mexico, the IMC is in charge of the monitoring center of bridges and intelligent structures (CEMPEI), which is responsible for monitoring the infrastructure of the main road corridors in the country. One of the most prominent cases is monitoring and load testing of El Carrizo bridge (a project monitored by CEMPEI), in which a road accident occurred. Thanks to the IMC system, it was possible to perform a quick evaluation of the structure in order to put it into service with the necessary repairs, thus demonstrating the benefit of the system.

In other countries, such as Chile, after the last collapse events (Table 1), bridge revision and monitoring projects were initiated, highlighting that there are already monitored bridges there. It is necessary to expand IMC programs in order to increase the infrastructure covered and avoid fatal incidents.

1 Some conclusions are shown in [https://www.gob.mx/imt/es/videos/monitoreo-y-pruebas-de-carga-en-el-puente-el-carrizo](https://www.gob.mx/imt/es/videos/monitoreo-y-pruebas-de-carga-en-el-puente-el-carrizo). Mexican Institute of Transport (IMT) leads other examples about their practices. [https://www.gob.mx/imt](https://www.gob.mx/imt).  
2 An important local-newscasts published this information: [https://www.t13.cl/noticia/politica/video-pinera-destituye-al-director-obras-del-mop-caida-puente-osorno](https://www.t13.cl/noticia/politica/video-pinera-destituye-al-director-obras-del-mop-caida-puente-osorno)
In the USA, an article determined that they have a worn infrastructure, with lack of maintenance, and with a completed time of useful life [21]. This emphasizes the importance of an IMC, which allows establishment of the necessary maintenance for bridges.

In conclusion, it is necessary that in Colombia the bridge administration system (SIPUCOL) starts with the implementation of an IMC system for the bridge infrastructure connected to INVIAS, according to the importance and relevance of the structures along with their respective road corridors. Other factors to take into consideration are vehicular traffic, old age, lighting, budget for instrumentation, level of project information, location and typology.

4. Instrumentation, software and staff for an IMC System

4.1. Instrumentation
This section presents the status of instrumentation equipment, software and staff for bridges’ IMC systems. Table 3 describes instrumentation equipment together with measurement data.

| Equipment                        | Measurement data               |
|----------------------------------|--------------------------------|
| Anemometers                      | Wind speed and direction       |
| Deformeters                      | Deformation                    |
| Load cells                       | Tension                        |
| Scouring sensor                  | Scouring                       |
| Settlement sensor                | Settlement                     |
| Temperature multipoint FBG sensor| Deformation and temperature    |
| Tiltmeter                        | Tilt                           |
| Triaxial accelerometers sensor   | Acceleration                   |
| Type K thermocouple              | Temperature                    |
| Uniaxial accelerometers sensor   | Acceleration                   |

4.2. Software
The necessary software must analyze the data and compare it with the ranges established by professionals, thus issuing an alarm when the bridge does not behave optimally. Alonso et al [22] recently presented a review of internet-based technologies of things (IoT) that are currently used. In summary, they can originate in three ways: through the purchase or rental of software developed by companies in the sector; through own developments of data analysis programs and / or the use of free license software oriented to data analysis.

4.3. Minimum professional staff
The personnel require strong qualifications for the project. The main staff is described as follows:

| Staff                              | Experience | Specialist                                |
|------------------------------------|------------|-------------------------------------------|
| Civil engineer                     | 10 years   | Structures and bridge design              |
| Telecommunications or electrical engineer | 5 years   | N/A                                       |
| Systems engineer                   | 10 years   | Programming or software development       |
| Installation technicians           | 2 years    | N/A                                       |
5. Equipment, typology and benefits of case study

5.1. Equipment

The following table describes the equipment of instrumentation used in the case study, the measurement data and its location in the structure. Later in the chapter, the typology of the case study is addressed, before comparing the costs related to the instrumentation and the final cost analysis.

| Equipment                                      | Measurement data            | Location                      |
|------------------------------------------------|----------------------------|-------------------------------|
| -Load cells                                    | Tension                     | Cable                         |
| -Temperature multipoint FBG sensor             | Deformation and temperature | Deck                          |
| -Type K thermocouple                           | Temperature                 | Deck and cable                |
| -Deformeters                                    | Deformation                 | Deck, towers and anchorage    |
| -Uniaxial accelerometers sensor                | Acceleration                | Cable                         |
| -Triaxial accelerometers sensor                | Acceleration                | Anchorage block and point     |
| -Anemometers                                   | Wind speed and direction    | Towers and deck               |
| -Tiltmeter                                     | Tilt                        | Top of the tower              |

It should be noted that no equipment was used for scour control, however in [23] relevant information for the selection of the scour sensors was obtained. Additionally, and in accordance with the equipment installed on site, the author concludes: “...Both the shallow foundation experiment and the deep foundation experiment give promising results that the accelerometer can be used to predict bridge failure as well as tilt-meter and sonar sensor.” … “approach is proved to be effective to analyze the accelerometer data as they showed significant change when the scour depth reached the bottom of the column, and the column started to settle and rock” [23, p. 87] … “the scour monitoring system will result in a program that is successful to ensure the safety of the bridge and of the traveling public”… [23, p. 271].

5.2. Typology

The approximate typology of the case study corresponds to a cable-stayed bridge 400 meters in length, with a main span of 250 meters and entrance and exit spans of 80 meters. The deck has a useful width of 15 meters and a height of 1.40 meters. The bridge is a harp and fan type. The separation of the points of support of the deck is 10 meters. Two beams every 4.50 meters support the cross section of the deck. The deck is supported by two towers and at its ends by two counterweights, to which some braces are anchored. The bridge has an orthotropic deck formed by two lightened main longitudinal ribs to which the braces are anchored, joined by transverse beams every 4.50 meters and an upper slab as a board. The batteries have a type H geometry; each column is responsible for a cable plane. The stack has two transverse braces 1.50 meters high and 1.30 meters wide, with concentric post-tensioning. The lower brace supports the deck with two insulators. The bridge is not compensated in its construction, so it has two counterweights at its ends that anchor six braces.
5.3. Benefits

The main benefit of an instrumentation, monitoring and bridges control system lies in having the data on the behavior of the structure in real time, analyzing and storing it, so it can be known if the structure is behaving properly and in the right ranges, and when it stops behaving in that way. It is advisable to begin the IMC from the construction of the structure, in order to acquire the data of its behavior, and perform the installation of embedded equipment in the concrete. Even during its construction, stage it is possible establish the ranges of the structure’s behavior, determining the possibility of an imminent collapse, and solving the problems described in the introduction. In that order of ideas, with the data of the structure it is also possible to verify the state and behavior of isolated elements, which may be susceptible to maintenance or reinforcement, even warning of the malfunction of those elements with the goal of making preventive corrections, avoiding invasive maintenance and additional expenses that could close road corridors. The instrumentation also generates early warnings of scour, as mentioned in previous chapters, which allows us to know a bridge’s state after earthquakes or road accidents and geological movements. The IMC of bridges takes on special relevance considering that each year the country’s infrastructure sees greater aging, increasing the need to perform maintenance where the structure requires. Additionally, climate change increases the scour factors on the structure. Along those lines, it is important to highlight the following Table 6, which shows 63 real cases of collapse registered in Colombia since 1986.

| Main Cause                        | Number of bridges | Percentage |
|----------------------------------|-------------------|------------|
| Structural and design deficiency | 6                 | 10%        |
| Scouring                          | 15                | 24%        |
| Overload and impact              | 3                 | 5%         |
| Terrorist attacks                | 20                | 32%        |
| Landslides, growth, etc.         | 15                | 24%        |
| Lack of maintenance              | 1                 | 2%         |
| Deficiencies in construction or auditing | 3     | 5%         |
| Total                            | 63                |            |

Table 6. Causes of collapse of bridges in Colombia [24].

In this way, the need for an instrumentation, monitoring and control system of bridges is clear, particularly in considering the investment in the infrastructure of the country, in that it would allow us to know, anticipate, and facilitate the maintenance of the structures and therefore mitigate or reduce the collapse events that may happen in the future. [25].

The IMC system has another benefit associated with the clarification of investigations and responsibilities in cases where the structure was not built with the established materials, due to the ease of the analysis of the structure. It is also possible to share the data analysis with other entities like national risk and disaster management unit UGRD.

Below, a cost and risk graph shows the IMC level and the level of IMC efficiency. Note the point “IMC adequate,” which represents the appropriate point between the level of efficiency and level of the IMC (see Figure 1).
6. Interest groups Colombia

Interest groups in Colombia are divided in two: state entities and private organizations, which are described in the table below.

7. Costs

Through a financial exercise on the real costs of a bridge in recent construction in Colombia, the following values for the typology described above were found. The cost of a bridge IMC system for this typology corresponds to a percentage around 6.8% to 7.1% of the total value of the bridge’s construction, with a high level of instrumentation. However, if we take into account the total value of the contract, which includes social, property and environmental management, the percentage of the IMC system is around 4.4% to 4.6%. The percentage that corresponds to the instrumentation of the bridge is around 58.9% to 60.9% of the total value of the IMC contract and the remaining percentage of 39.1% to 41.1% corresponds to staff.

![Figure 1. Costs vs Risks](chart.png)
### Table 7. Interest groups in Colombia.

| State entities | Because | Due to |
|----------------|---------|--------|
| INVIAS         | Formulation and estimation of costs of IMC systems of bridges that make or will be part of the network in charge of the entity. In the programming of the maintenance, monitoring and checking of the state of the infrastructure of bridges that are attached to the entity. | In compliance with its functions according to Decree 2056 and 2067 of July 24, 2003. |
| National Infrastructure Agency, ANI | Formulation, estimation of costs of projects that make or will be part of road concessions. | In compliance with its functions according to Decree 4165 of November 3, 2011 In case of any irregularity or investigation of the project. |
| Control entities, Prosecutor's Office, Procuracy Office and Comptroller's Office | Clarification of investigations and controversies in case of collapse of a structure that uses the IMC system. | In case of any irregularity or investigation of the project. |
| UGRD National risk and disaster management unit | System of early warnings and verification of the state of the structure after natural disasters or road accidents that involve structures with IMC. | Coordination of activities in the event of a disaster. |

| Private Organizations | Because | Due to |
|-----------------------|---------|--------|
| Construction contractors | Start-up of the IMC system of bridges during the construction stage, with early warnings in case of the structure’s collapse. | Due to the responsibilities acquired in the contract. |
| Road Concessions | Start-up of the IMC system of bridges during the construction stage, with early warnings in case of the structure’s collapse. | Due to the responsibilities acquired in the contract. |
| Insurers | Start-up of the IMC system of bridges during the construction stage, with early warnings in case of the structure’s collapse. Offering the opportunity to reinforce the structure, or safeguard the lives of workers or third parties who may be involved, avoiding the payment of policies Provision of data due to the action of repetition after the payment of policies, in order to avoid costly and / or delayed investigations to establish responsibilities. | Payment of indemnities associated with policies of responsibility, quality, stability, being those affected due to the payment of claims. Legal defense of the insurer. |
8. Conclusions
The instrumentation, monitoring and control of bridges is necessary, in order to avoid and mitigate the problems related to the collapse of the structures, since identifying the deformations that are generated in early phases allows the generation of alerts to the community in general, fundamental information for the authorities in charge i.e. INVIAS and ANI, control authorities, and insurers in the case of Colombia, thereby allowing the necessary repetition actions due to action or omission.

Additionally, this article teaches the benefits related to the maintenance and control phase of structures due to the specific technical information obtained on damages caused by earthquakes, road accidents, overloads, scour or geological events. Further, in an eventual investigation, information from the IMC allows the easy solution of contractual problems related to the technical behavior of the infrastructure, in such a way that the responsibility of anyone involved can be identified.

The IMC is not restricted only to the behavior of the substructure and superstructure, but can also implement slopes, retaining walls and other elements of civil works. However, a particular pre-feasibility study is required for each project due to the factors specific to each type of project. It is also advisable to plan the IMC from the formulation of the building project, since it is advisable to generate a budget and schedule of technical and administrative tasks that fit the needs of the project. Therefore, it is necessary to have the collaboration of the professional structural designer of the bridge.

The main factor that determines the direct cost of the IMC systems is the type of bridge; additionally, the analysis and maintenance of the resulting data throughout the life cycle of the bridge must be considered as an operational cost of the system. Currently these costs are not considered in the budget, and it is recommended that they be done through independent contracts. For the typology described it conclude that the investment cost of IMC system with a high level of instrumentation is close to 7% of the construction value of the bridge.

Finally, the cost vs. risk is outlined where, at a higher investment cost in the IMC system, the risk in the structure is lower. In the same way, the efficiency level function indicates that an excessive level of instrumentation generates financial inefficiency in the investment. The graph shows a point called ADEQUATE IMC, the point where the two functions intersect and is the level of instrumentation suitable for the bridge. It must be said that this chart applies to any bridge that requires an IMC system.

References
[1] El Nuevo Diario 2018 Los derrumbes de puentes más mortíferos de los últimos 20 años Available: https://www.elnuevodiario.com.ni/internacionales/472161-ultimos-derrumbes-mortiferos-puentes/
[2] Farrar C and Worden K An introduction to structural health monitoring 2006 Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences vol 365 no 1851 pp 303-315
[3] Hernández J M 2018 Las empresas que responderían por el colapso del puente de Chirajara El Espectador Available: https://www.elspectador.com/economia/las-empresas-que-responderian-por-el-cola-5o-del-puente-de-chirajara-articulo-733921
[4] Gómez Fuentes A 2018 Diez puentes se han desplomado en Italia en los últimos cinco años Diario ABC Available: https://www.abc.es/internacional/abci-diez-puentes-desplomado-italia-ultimos-cinco-anos-201808142109_noticia.html
[5] El Nuevo Herald 2018 Diseño y mantenimiento del puente de Génova, Italia, están bajo sospecha Available: https://www.elnuevoherald.com/opinion-es/trasfondo/article217070475.html
[6] García J M, Ospina J and Graciano E A 2014 Evaluación técnica de los puentes en la infraestructura vial del departamento de Antioquia Ingeniería Solidaria vol 10 no 17 pp 49-54
[7] Parkasiewicz B, Kadela M, Bętkowski P, Sieńko R and Bednarski Ł 2007 Application of structure monitoring systems to the assessment of the behaviour of bridges in mining areas
IOP Conference Series: Materials Science and Engineering vol. 245 no 3 p 032018

[8] Palomino C 2018 Ética y corrupción de la ingeniería estructural Asociación Colombiana de Ingeniería Estructural Available: www.aciescolombia.org

[9] El Espectador 2018 Fiscalía abre investigación por desplome del puente Chirajara, en vía al Llano Available: https://www.elespectador.com/noticias/judicial/fiscalia-abre-investigacion-por-desplome-del-puente-chirajara-en-al-llano-articulo-733619

[10] Caracol Radio 2018 Lo que quedo del puente Chirajara será dinamitado, según Covianides 6 AM Hoy por Hoy Available: http://caracol.com.co/radio/2018/02/23/nacional/1519383146_948387.html

[11] Benitez K 2018 Gisaico contrató con QBE la póliza “Todo Riesgo Construcción” La República. Available: https://www.larepublica.co/economia/gisaico-contrato-con-qbe-la-poliza-todo-riesgo-construccion-2589525

[12] Caracol Radio 2018 Coviandes tenia todos los seguros exigidos para obras como el puente de Chirajara Available: http://caracol.com.co/radio/2018/01/17/nacional/1516188907_972678.html

[13] Caracol Radio 2018 Pólicas son suficientes para cubrir el siniestro del puente de Chirajara Available: http://caracol.com.co/radio/2018/11/07/nacional/1541553265_786059.html

[14] El Telégrafo 2017 Nuevo puente une a más 12 comunidades de Napo Available: https://www.eltelegrafo.com.ec/noticias/regional/1/nuevo-puente-une-a-mas-12-comunidades-de-napo

[15] Caracol Radio 2017 En riesgo de colapso, se encuentra viaducto entre Boyacá y Casanare Caracol Radio Available: http://caracol.com.co/emisora/2017/06/14/tunja/1497439053_572341.html

[16] García R 2018 Megaproyectos y desastres ambientales: ¿qué está pasando? UN Periódico Digital Available: http://unperiodico.unal.edu.co/pages/detail/megaproyectos-y-desastres-ambientales-que-esta-pasando/

[17] Diario ABC 2018 Ya son 43 muertos en el puente Morandi en Génova Available: https://www.abc.es/internacional/abci-morandi-milano-quince-muertos-dani-43-muertos-puente-morandi-genova-201806191815_video.html

[18] El Universo 2014 Puente colapsa en Napo; doce personas resultaron heridas Available: https://www.eluniverso.com/noticias/2014/04/04/nota/2596646/puente-colapsa-napo-12-personas-resultaron-heridas

[19] Instituto Mexicano de Transporte 2017 Monitorear Puente y Estructuras de México Available: https://www.gob.mx/imt/articulos/monitorear-puentes-y-estructuras-de-mexico?idiom=es

[20] Klikowicz P, Salamak M and Poprawa G 2016 Structural health monitoring of urban structures Procedia engineering vol 161 pp 958-962

[21] Infrastructure report card 2017 Infrastructure report card Available: https://www.infrastructurereportcard.org/wp-content/uploads/2017/01/Bridges-Final.pdf

[22] Alonso L, Barbarán J, Chen J, Díaz M, Llopis L and Rubio B 2018 Middleware and communication technologies for structural health monitoring of critical infrastructures: A survey Computer Standards & Interfaces vol 56 pp. 83-100

[23] Braud J L, Hurlebaus S, Chang K A, Yao C, Sharma H, Yu O Y, Darby C, Hunt B E and Price G R 2019 Realtime monitoring of bridge scour using remote monitoring technology Available: https://static.tti.tamu.edu/tti.tamu.edu/documents/0-6060-1.pdf

[24] Muñoz Díaz E E 2002 Estudio de las causas de colapso de algunos puentes en Colombia Ingeniería y Universidad vol 6 no 1 pp 33-48

[25] Correa M V 2017 Así avanza la construcción de cinco grandes puentes El Colombiano Available: http://www.elcolombiano.com/co/obra-de-cinco-grandes-puentes-en-colombia/L16695278