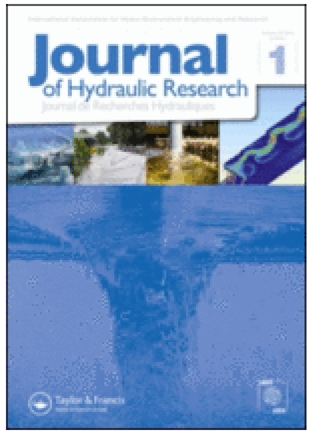

Santa María and the first pier scour formulas

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Keywords:	Biography, history, scour, hydraulics, bridges

Concepción, March 12th, 2024

Dear Editor

I appreciate the work done by the three reviewers and the associate editor, who brought up many valid and interesting comments and valuable suggestions on the submitted manuscript "Santamaría and the first pier scour formulas". In my opinion, the manuscript is now suitable for publication in the Journal of Hydraulic Research, after the following corrections. All observations and comments by the reviewers have been addressed. In the following, all suggestions and comments are commented point by point.

Yours sincerely,

Oscar Link

Answers to comments by Reviewer: 1

Obs. 1: GENERAL

This work deals with the first (as stated by the author) scour (I would think pier scour) formulas presented by the Chilean Santa Maria. As is, it needs lots of improvements, mainly in terms of the English usage, deletion of repetitions, drop of too detailed info, and improvement of the citations in the JHR style. Please have a close look at the attached review comments.

Ans. 1: Thank you. Improvements attending all the review comments in the attached file were included.

DETAILS

Obs. 2:. Given that mainly piers are considered in terms of scour, use improved title

Ans. 2: Thank you. The title was changed to: Santamaría and the first bridge pier scour formulas.

Obs. 3: . Keywords in ABC

Ans. 3: Thank you. Done!

Obs. 4: Drop details as in Line 43-44 (Page 3), 50-56 (Page 6)

Ans. 4: Thank you. Done.

Obs. 5: . Give source details for Fig. 1

Ans. 5: The source details for Fig. 1 is: Instituto de Ingenieros de Chile (1919). It was included in the Figure caption.

Obs. 6: Improve 'critical' such as on Line 30, p.5

Ans. 6: Thank you. Critical refers to the threshold or critical condition for initiation of sediment motion. An explanation was included in the text.

Obs. 7: Translate all text in Figs. 2-4 in an Appendix.

Ans. 7: Thank you. Figures were translated and included in Appendix.

Obs. 8: Number all equations, such as on p. 5

Ans. 8: Thank you. Done.

Obs. 9: Do you really need to state all dams considered by Santa Maria on p. 6? Nobody of the readers would locate them...

Ans. 9: The author agree with the reviewer, thus the name of the bridges studied by Santa María were dropped from the text in page 6.

Obs. 10: Page 7, Line 31, Santa Maria (1908) is not cited in the List of references

Ans. 10: Apologize, there was a typo error. The quotation refers to Santa María (1909).

Obs. 11: Cite Bazin and Du Buat

Ans. 11: Thank you, both references were included. These are:

Bazin, H. (1897). Etude d'une nouvelles formule pour calcules le débit des canaux découverts. Ann. des Ponts et Chaussées, 67(4):20-70.

Du Buat, P. L. G. (1779) Principes d'hydraulique. Paris: L'imprimérie de Monsieur, France, 1st ed. (in French).

Obs. 12: What is 'general erosion'? page 9, Line 38

Ans. 12: Apologize for this misunderstanding. With general erosion it was meant general scour and it was corrected along the text.

Obs. 13: All citations need volume, issue and page numbers

Ans. 13: Thank you. Done.

Obs. 14: Translate all non-English cites into English in parentheses

Ans. 14: Thank you. Done.

Obs. 15: Chabert and Engeldinger (1956) is incomplete, as is Keutner (1932)

Ans. 15: The complete references were included, these are:

Chabert, J., and Engeldinger, P. (1956). Etude des affouillements autour des piles de ponts. Lab. Nat. d'Hydr. Chatou, Serie A, Octobre, pp.: 128.

Keutner, C. (1932). Strömungsvorgänge an Strompfeilern von verschiedenen Grundrissformen und ihre Einwirkung auf die Fluss-Sohle. *Die Bautechnik*, 10(12):161-170.

Obs. 16: What about Santa Maria (19001d)

Ans. 16: Apologize for this missunderstanding. All Santa María's articles were revised, as well as those citations in the text.

Obs. 17: CONCLUSION

The Author needs to improve his submission adequately thereby following closely the JHR Authors' Guidelines. Once resubmitted, I will have another look at his work.

Ans. 17: Thank you for all your comments which helped to improve the quality of the MS.

Answers to comments by Reviewer #2

Comments to the Author

Obs. 1: Please, refer to the attached document.

Ans. 2: Thank you very much for all your comments which helped to improve the quality of the text. All of them are considered in the new version of the MS.

Answers to comments by Reviewer #3

Obs. 1: The author evokes the life of Domingo Santa María (1854-1919), who was in charge of planning and supervising of the main Chilean railway and dedicated his 20 last years to academic teaching at the University of Chile. In particular, from his experience in numerous river crossings he proposed two formulas: one for general erosion in riverbed and another for the scour depth along bridge piers. The author claims that these formulas are the first to be developed in that field.

To be interesting for the reader, this type of biography must meet some criteria:

- Introduce a personality known widely enough to arouse the interest of most of the readers.
- Present, at least briefly, the historical and technical context of the time.
- Explain the new theoretical and practical inputs by the personality, emphasizing the novelties of the new approach by comparison with the ones prevailing in the time. This implies that not only the results are given but also the reasoning that led the person to this result.
- Present in what these contributions influenced the science or the technology in the time and in the future.

I am afraid that none of these criteria will be met:

- The personality is not well-known at international level and his name does not appear in any classical textbook.

- His life is recounted like in an obituary and neither the historical nor the technical context is presented: for instance, explanations about the difficulties of developing a railway in the Chilean context could be more developed, otherwise than quoting never-ending series of bridge collapses, without any interest for the reader, especially since these disasters are not located, for example on a map.

- The two “novel” formulas are presented as they are, without any explanation. For knowing their derivation, the reader is invited to refer to two Santa Maria’s papers in Spanish, some excerpts of which are given in low-quality facsimile. That means that the reasoning of the author of the formulas is inaccessible to most of the readers.
- An “analysis” of the scour formulas is announced but this analysis is limited to a

description of measurement devices of water surface velocity and to the old table of critical velocity by Du Buat and Telford. No comparison is made between measurements and result of the new formulas. There is also no comparison between the formulas and the previous and subsequent approaches. For example, Du Buat's early works are just quoted but nothing more. The only comment is that the new approach is "similar to the Du Buat type formula for sediment transport but much advanced than subsequent scour formulas based on regime theory", but no evidence of that is proposed.

In the end the paper does not bring anything interesting for the JHR audience.

Ans. 1: The personality of Santa María was well known and important for Chile and the international scientific community, as he led the engineering projects allowing the expansion of the Chilean railway from Santiago to the southern part of the country, and later on, as an outstanding university scholar. Santa María was faculty member and Dean of the Faculty of Physical and Mathematical Sciences at Universidad de Chile. During his career, he published over 40 technical articles, and was part of the organizing committee of the first Pan-American Scientific Congress. Thus, it can be concluded that by the end of s. XIX and beginning of the s. XX Santa María was known widely enough to arouse the interest of most of the readers.

The historical and technical context is especially highlighted in the introduction, with a detailed literature review providing clear evidence on the fact that Santa María published his bridge scour formula almost 40 years before other formulas (the oldest known bridge scour formula is that proposed by Inglis in 1944, while Santa María proposed his bridge scour formulas in 1901). Santa María's formula was based on field evidence collected at a very high number of study sites even for today circumstances, namely 56 bridges, providing evidence of the rigorousness of Santa María's work.

The reasoning that led Santa María to his formulas was included in Section 3 emphasizing the novelties, such as the application of, to that time, recently proposed formula by Bazin (1897) clearly showing that Santa María worked up to date in the state of the art. The names of the study bridges are presented in a Table and the location of the study sites is shown in a map.

Explanations about the difficulties of developing a railway in the Chilean context were more developed, and a map with the location of the bridges studied by Santa María is provided.

The derivation of both formulas shown in Fig. 2 is translated and included in the Appendix.

A comparison of results obtained with Santa María's formula and other bridge scour formulas is included.

The form of the paper

Obs. 2: The section 3 "The scour formula by Santa María" that is supposed to present the essential of the paper consists of a simple description of two papers by Santa Maria. Regarding the first paper, the 1901 paper, the content of each of the six chapters is mentioned without any criticism. For example, the description of the first chapters of this 1901 paper is presented as follows: "After an introduction in Chapter I, Chapter II is dedicated to providing a description of mountain rivers behavior based on observations of Chilean rivers located between Maipo and Toltén. Chapter III presents …". The presentation of next chapters is worse as they consist of a long series of example of river scours and bridge collapses without any effort to systematize and classify the information.

Ans. 2: Thank you. The author agrees with this observation. The section 3 was changed substantially to better present the scour formulas by Santa María. In particular, the reasoning that led Santa María to his formulas was included in Section 3 emphasizing the novelties, such as the application of, to that time, recently proposed formula by Bazin (1897) clearly showing that Santa María worked up to date in the state of the art. The names of the study bridges are presented in a Table and the location of the study sites is shown in a map. The derivation of both formulas shown in Fig. 2 is translated and included in the Appendix. A comparison of results obtained with Santa María's formula and other bridge scour formulas is included.

Answers to comments by the AE

Obs. 1: I would like to thank the author for letting us know about the work of Santa Maria, who appears as not well known.

Ans. 1: Thank you.

Obs. 2: However, as outlined by the reviewers, in its current form, the paper cannot be accepted. The content should focus more on the scientific achievements, and the quality of the figures should be seriously improved.

Ans. 2: I appreciate the comments by the three reviewers, all of which were attended in the revised version, focusing more on the scientific achievements.

Obs. 3: Moreover, I was wondering whether such a contribution could be supported by other members of the Latin America Division if the intention is to put to the front a rather unknown researcher who would deserve more recognition.

Ans. 3: The author was invited keynote speaker at the XXVI Chilean Conference on Hydraulics, held in October 2023, with the presentation entitled: Design of Chilean railway bridges by the end of the s. XIX for disseminating the pioneer work done by Santa María. The audience was very positive about the findings and the Chilean Society of Hydraulics supports this work and recognize the achievements by Santa María. The author will also present the work by Santa María at the XXXI Latin American IAHR Conference, to be held in

Medellín, Colombia in October 2024. The publication of this MS in the JHR would certainly recognize the contribution of Santa María, and at the same time, reach a broader audience worldwide.

Santa María and the first pier scour formulas

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Santa María and the first pier scour formulas

Santa María and the first pier scour formulas

ABSTRACT

Domingo Santa María was the first to present pier scour formulas, one for the estimation of general scour or bed degraddation in rivers and another one for the estimation of maximum local scour depth at a bridge pier. His analysis was based on field observations at 56 bridges crossing Chilean rivers, with especial attention to the behaviour of railway bridges under conditions imposed by extreme floods. Santa María dedicated almost 20 years to the public service and another 20 years to the academy. Among several different tasks for the Chilean governments and the Ministry of Public Works, he was in charge of planning and supervising the construction of the main railway, connecting Santiago with the southern part of the country over ca. 1000 km. In the present paper, the pioneer scour formulas by Santa María are analysed and compared with other, well established scour formulas to highlight Santa María's outstanding contribution to the development of hydraulic engineering.

Keywords: Biography, bridges, history, hydraulics, scour, sediment, water.

1 Introduction

Scour at bridge elements is one of the most complex, fascinating and researched topics in hydraulics, first started by Durand-Claye (1873) and Engels (1894) through exploratory flume experiments that provided evidence to solve very basic and practical engineering questions such as: what pier shape is more favourable to prevent scour: rectangular, round nosed, lenticular, ogival, etc?, or, important for scour protection: where does the maximum scour depth around a bridge pier occur: at the pier front, at the sides, or at the pier back? A 25-years long gap of studies on the bridge pier scour is detected between 1895 and 1920. Presumably, scholars were dedicated to study the flow at piers with focus on the backwater effects for navigation. Studies and analysis of scour for specific bridges were published by Rehbock (1921) on the German river Wiesent near the city of Nürnberg, and by Yarnell and Nagler (1931) on the North Carolina standard reinforced concrete bridge pier. Keutner (1932), Tison (1940), Ishihara (1942), Chabert and Engeldinger (1956), as well as Laursen and Toch (1956) published detailed characterizations of scour hole geometry for a number of different experimental conditions, and were able to identify effects of flow velocity, flow attack angle, flow depth, sediment size, pier shape and pier length on scour. Laursen and Toch (1956) stated: "Neither these early experiments nor subsequent studies by various investigators in various countries have been sufficiently general to obtain the desired result – a means of predicting scour in the field." The oldest scour formula presented in the famous state of the art paper by Breusers *et al.* (1977) as well as compared by Sheppard et al. (2014) is that by Sir C. Inglis (1944, 1949), which is based on Lacey's method (Lacey, 1929) of estimating regime depth of flow in loose bed alluvial rivers (Kothyari, 2008), and field data of 17 bridges in India and Pakistan collected between 1924 and 1942.

Nearly a century before Inglis (1949) published his bridge pier scour formula, the golden age of rail started, promoted by the industrial revolution. In the second half of the XIX century the Chilean economy boomed thanks to the saltpeter export and thus the country was able to put forward the development of the national railways for the transportation of minerals to the ports at the Pacific Ocean, and to achieve the connectivity of the main city of Santiago with the northern part of the country, and with the far South (Oppenheimer, 1982). As the main Chilean longitudinal railway along the Central Valley crosses important rivers that flow from the Andes to the Pacific Ocean, the construction of bridges was especially relevant to achieve the connectivity goal. In doing so, several national e.g.: Juan Slater Co., Albarracín y Urrutia Co., as well as foreign, international companies were asked by the Chilean governments to build different railways, e.g.: Manby & Co built the Arauco Railway and Biobío bridge at Concepción (Manby, 1892), The North and South American Construction Company from New York built ten new railroads totalizing 1175 km (Edwards, 2001). Main difficulties for achieving the construction of the railways and particularly, their bridges is related to the fact that no electricity was available neither automobiles for transport of materials. Especially challenging was the construction of bridges foundations by means of screw-piles, small hydraulic-jet, or concrete piers in wrought-iron cylinders sunk by machine diggers.

The Chilean engineer Domingo Santa María was in charge for the planning, supervision, construction and maintenance of several railways and bridges built by the end of the XIX century. He dedicated especial attention to the design of the railway bridges located in Central-South Chile. As in this zone floods are frequent and severe, many bridges partially collapse during construction or shortly thereafter. Santa María was concerned about scour as one of the main causes of bridge collapses. In a first communication, Santa María (1901a,b,c,d) presented his empirical formulas as part of an analysis of scour at 56 different bridges under conditions imposed by extreme floods such as those occurring in 1877, and 1888. After an extended analysis of scour at bridges considering the extreme flood occurred in 1900, Santa María proposed his scour formulas in 1908 at the fourth Latin-American and first Pan-American Scientific Congress, held in Santiago de Chile (Holmes, 1909).

In this paper, the ideas and work of the Chilean engineer, Domingo Santa María (1854-1919) are revised. The next section presents a brief biography of Santa María, who developed his career after graduating as Geographic Engineer in 1874 and as Mining Engineer in 1875, both at Universidad de Chile, and as Civil Engineer in 1878 at the University of Ghent. Thereafter, the main ideas and works on scour by Santa María are revised, including the development of the first bridge scour formulas. Next, Santa María's formula for estimating the maximum scour depth at bridge piers is analysed and compared with modern formulas.

2 Brief biography of Domingo Víctor Santa María

Domingo Víctor Santa María Márquez de la Plata was born on March 6th, 1854, at Santiago de Chile. His father, Domingo Santa María, was an outstanding Chilean politician, who was president in the period 1881-1886. At the age of 20 years, Santa María graduated as Geography Engineer at Universidad de Chile, and one year later he graduated as Mining Engineer at the same university. Thereafter he moved to Belgium, where he graduated as Civil Engineer in 1878 from the University of Ghent (note that its Hydraulics Laboratory was founded in 1935 by Prof L.J. Tison). Back from Europe, Santa María worked as professional engineer in several railways, ports and bridges projects for the Chilean government, and in parallel started a political career, being member of the House of Representatives in two consecutive periods, 1879-1884 and 1885-1888.

He was General Director of Public Works in 1888, after which he become technical inspector in charge of the acquisition of trains for the Chilean state. For this purpose, he lived for two years in Europe. Back in Chile again, he assumed in 1891 a second period as General Director of Public Works, until May 14th, 1895 (Instituto de Ingenieros, 1919).

Santa María was a faculty member at Universidad de Chile between 1899 and 1919. He teached the courses “bridges” and “railways”, and was dean of the Faculty of Physical and Mathematical Sciences between 1907-1909. As a prolific scholar, Santa María published over 40 communications in the Anales de la Universidad de Chile and the Anales del Instituto de Ingenieros de Chile (https://revistas.uchile.cl/index.php/AICH/issue/archive) on diverse engineering topics, such as planning of railways, the use of mild steel in railway bridges, debris flows, scour at bridge elements, and the supply of the drinking water in cities.

Santa María passed away on December 11th, 1919, at the age of 65 years.

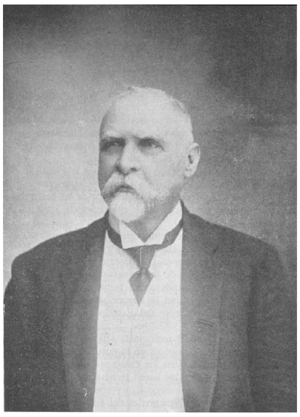

Figure 1. Domingo Víctor Santa María (1854-1919) (Source: Instituto de Ingenieros de Chile, 1919)

3 The scour formula by Santa María

3.1 The 1901 paper

In a series of four parts (Santa María, 1901a, 1901b, 1901c, and 1901d) entitled "Puentes Chilenos" (Chilean bridges), Santa María exposed observations on the behaviour of different rivers located in Central-South Chile, providing pertinent recommendations to practical engineers with special focus on the foundations. After an introduction in Chapter I, Chapter II describe the behaviour of mountain rivers based on observations of Chilean rivers located between rivers Maipo and Toltén. Chapter III presents a formula for general scour, Chapter IV distinguishes between riverbeds admitting excavations for construction of foundations from those that require water pumping. Chapter V is devoted to an analysis of scour at bridge foundations under flood conditions, considering observations of the floods occurred in years 1868, 1877, 1878, 1884, 1885, 1888, 1898, 26-29 August 1899, and 1900. A total of 16 study cases were analysed, including the Cal y Canto Bridge, built by Spaniard conquerors in 1779 over the Mapocho River near Santiago, Chile, having collapsed several times (Rosales, 2019). Chapter VI was devoted to bridges with shallow foundations. A total of 35 additional study cases were analyzed, including the Maule Bridge over the Maule River near the city of Constitución, Chile, to which Santa María devoted a series of five communications on its construction in years 1898 and 1899 (Santa María, 1898 and 1899a,b,c,d), and the Biobío Bridge at Cerro Chepe in the city of Concepción, Chile, with 1899 m in length and a sandy streambed (Manby, 1892). Figure 2 shows the location of the bridges studied by Santa María. The bridges names are included in Table 1.

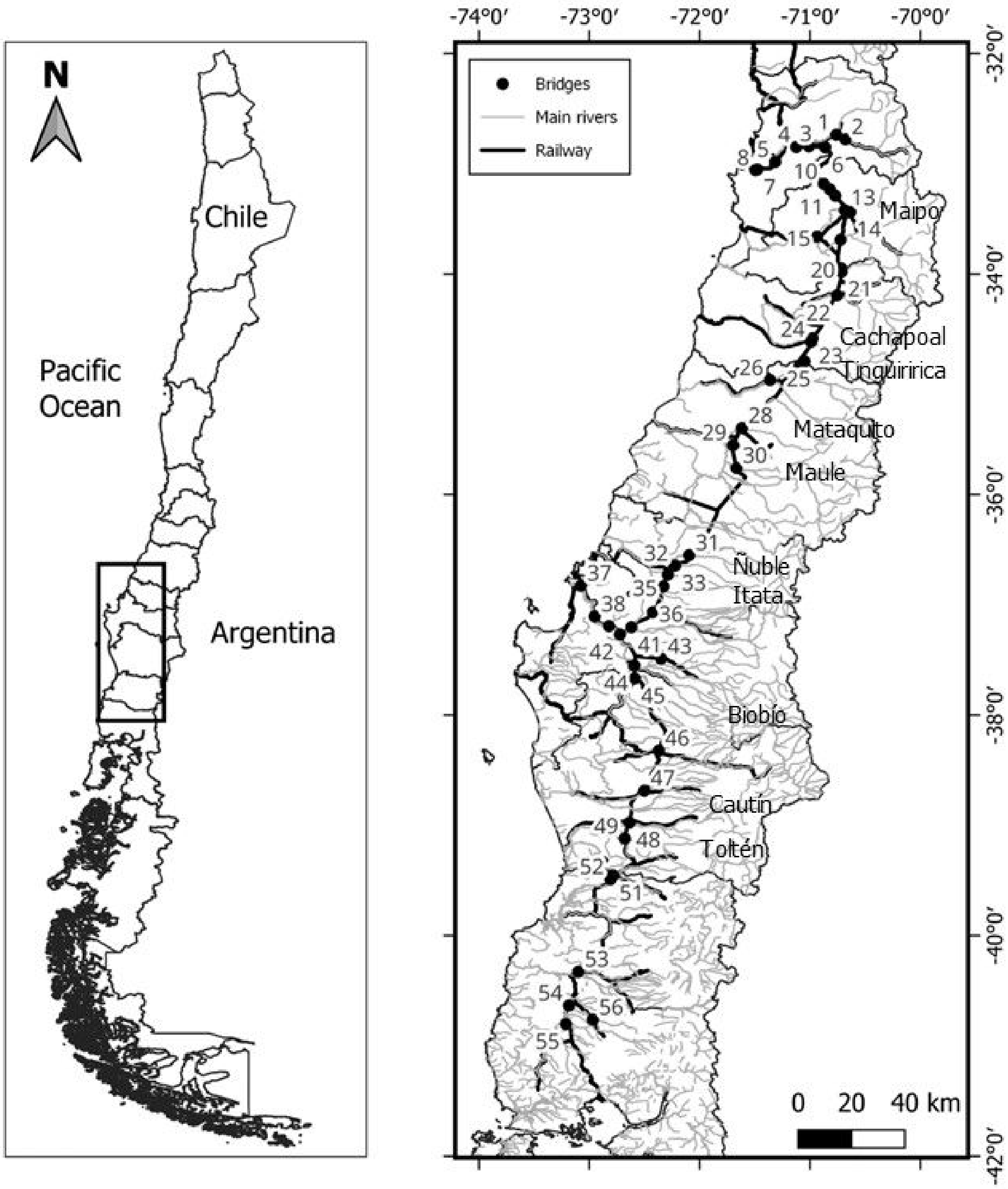

Figure 2. Location of the bridges studied by Santa María

Table 1. Bridges studied by Santa María.

Nr.	Bridge	Nr.	Bridge
1	SAN FELIPE	29	MAULE
2	CURIMÓN	30	BATUCO
3	LAS OVEJAS	31	ÑUBLE
4	RABUCO	32	NEBUCO
5	LIMACHE	33	CHILLÁN
6	LOS MAQUIS	34	COYANCO
7	PASO HONDO	35	PAL PAL
8	LAS CUCHARAS	36	MONTEAGUILA
9	EL TABLÓN	37	BIOBÍO AT CERRO CHEPE
10	CHACABUCO	38	QUILACOYA
11	LAMPA	39	GOMERO
12	COLINA	40	SANTA MARÍA
13	CAL Y CANTO	41	RÍO CLARO NEAR YUMBEL
14	LA PURÍSIMA	42	LAJA
15	MAPOCHO AT SAN FRANCISCO DEL MONTE	43	PAILLIHUE
16	MAIPO	44	BIOBÍO AT COIHUE
17	DE PALOS OVER THE MAPOCHO RIVER	45	RENAICO
18	DEL LITRE	46	EL SALTO
19	QUEBRADILLA, DE PATAGUAS	47	CAUTÍN
20	ANGOSTURA	48	TOLTÉN
21	SAN FRANCISCO	49	DONGUIL
22	CACHAPOAL	50	HUEQUÉN
23	ANTIVERO	51	LEFICAHUE
24	TINGUIRIRICA	52	CIRUELOS
25	CHIMBARONGO	53	RÍO BUENO
26	TENO SUR	54	RAHUE
27	TRONCOSO	55	FORRAHUE
28	LIRCAY	56	CANCURA

Santa María's reasoning for the development of his formulas starts by stating that applications are thought for bridges located along the Central Valley (as to the East the Andes and to the West the Coastal Cordillera would add significant additional difficulties to the development of railroads due to the high slopes), between Santiago city and Toltén River. Santa María points out that during floods the rivers in this area exhibit torrential flows and at the same time, the riverbeds are composed of gravel and boulders. For general scour, he proposes that the flow velocity at the bottom is able to produce general scour if the critical velocity for the inception of sediment motion is exceeded, defining the excess near bed flow velocity *V3* as the difference between the near bed flow velocity u_*, and the critical near-bed velocity for inception of sediment motion $u_{*,cr}$:

$$V3 = u_* - u_{*,cr} \tag{1}$$

Accordingly, Santa María observed that if u_* is less than $u_{*,cr}$ the streambed is in equilibrium and no general scour occurs, but if u_* is higher than $u_{*,cr}$, then there can't be equilibrium. The general scour depth, $z_{max,\,GS}$ was proposed to be proportional to the flow depth, H while the excess velocity needs to be counterbalanced by bottom friction and scour to achieve equilibrium. Santa María proposed:

$$\frac{z_{max,\,GS}}{H} = \frac{u_* - u_{*,\,cr}}{z_{max,\,GS}} \tag{2}$$

and thus, the general scour depth, $z_{max,GS}$ is:

$$z_{max,\,GS} = \sqrt{H(u_* - u_{*,cr})} \tag{3}$$

Further, in case of obstacles placed in the flow, Santa María recognized the formation of eddies that act enhancing scour locally, around the obstacle. He argued that according to the sounding literature, the scouring potential of the eddies increases with the average flow velocity squared, but he doubts such a relation between scour depth and flow velocity, based on unrealistic results he obtained in some applications. Santa María explains that increased internal friction caused by the sediment particles in motion as bed-load and suspended sediment might be responsible for a reduced scour, i.e. not proportional to the flow velocity squared. Next, Santa María proposed that the local scour depth is proportional to the surface flow velocity and to the near-bed flow velocity, as well as to the flow depth and the bed resistance due to friction. Taking the near-bed flow velocity as 0.65 times the surface flow velocity, u_s Santa María proposed the following empirical formula:

$$z_{max,\,LS} = H\frac{(0.65u_s - u_{*,cr})}{(u_s - 0.65u_s)} \tag{4}$$

where $z_{max,LS}$ is the maximum local scour depth at a bridge element (pier or abutment). Figure 3 shows the original derivation of both scour equations by Santa María (1901a).

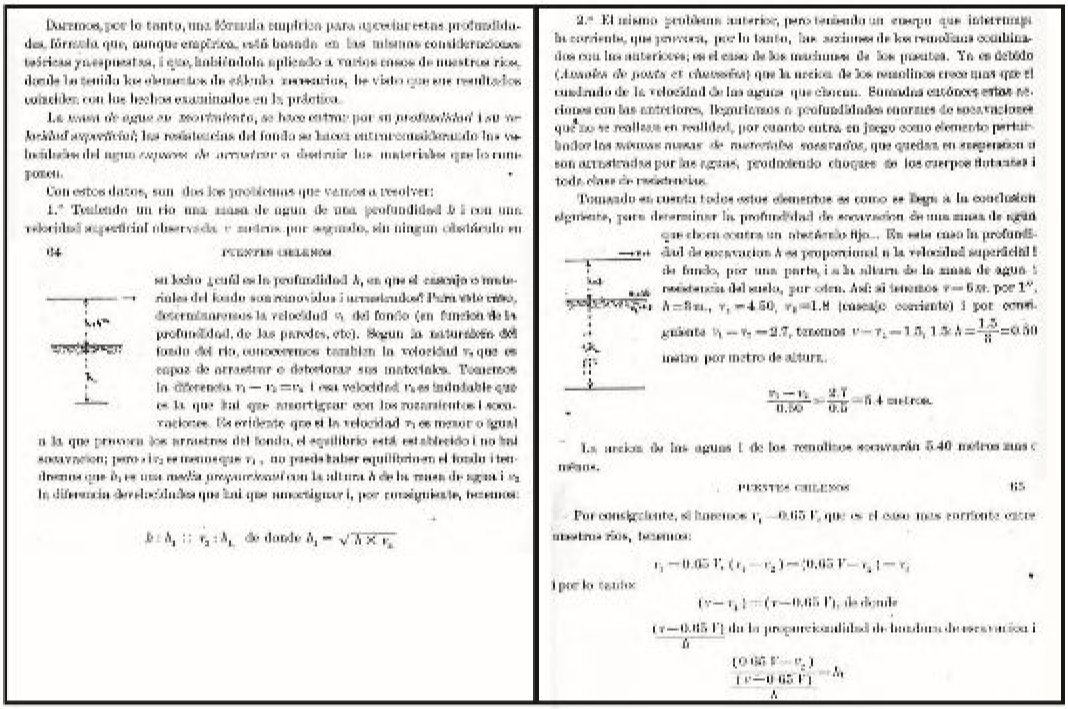

Figure 3. Derivation of scour formulas in Eqs. (2) and (4) by Santa María (1901a)

The proposed scour formulas were validated by comparing, for each study case, the length of foundations with the computed scour, and the occurrence of collapse during floods. Good agreement between the formula's results and the observed behaviour of bridges during floods was obtained.

3.2 The 1908 paper

This study was presented to an audience of over 600 participants at the Fourth Latinamerican and First Pan-American Scientific Congress (Holmes, 1909). His paper was entitled: "Subterranean waters of torrential rivers. Experiences in Chilean rivers" and was shortly thereafter published in Spanish (Santa María, 1909). The paper formally introduced the two scour formulas in Eqs. (2) and (4), for the estimation of general and local scour at bridges, respectively. Using data corresponding to the recently occurred extreme flood in August, 1900 a validation of the formula for estimation of general scour was presented for bridge sites at bridges Estero de Limache, Estero de Lampa, and Río Claro de Yumbel, and a validation of the formula for the estimation of the maximum scour depth at bridge piers was presented for bridges Mapocho en Talagante, Nuevo Río Claro de Yumbel, Tinguiririca Bridge, and Teno Bridge (please see Table 1 and Figure 2 for location of the bridges).

4 Analysis of Santa María's scour formulas

4.1 Data

Both scour formulas by Santa María are supposed to be applied considering conditions imposed by extreme floods. By the end of the XIX century, observations of maximum historical events were collected in Chile by public services in a non-systematic way. Usually, watermarks for some sites of interest were available. Besides, a compendium of the climates of Chile by Vicuña (1877) provided (and still does provide) a good description of floods and draughts during the XIX century (Jana et al., 2018).

The surface flow velocity was estimated by measuring the time taken by floats to cover a known distance. In the absence of such measurements, Bazin's formula (Bazin, 1897) was applied. Figure 4 shows extracts of Santa María's papers, with a description of surface flow velocity measurements (Santa María, 1899b) and the application of Bazin's formula (Santa María, 1909).

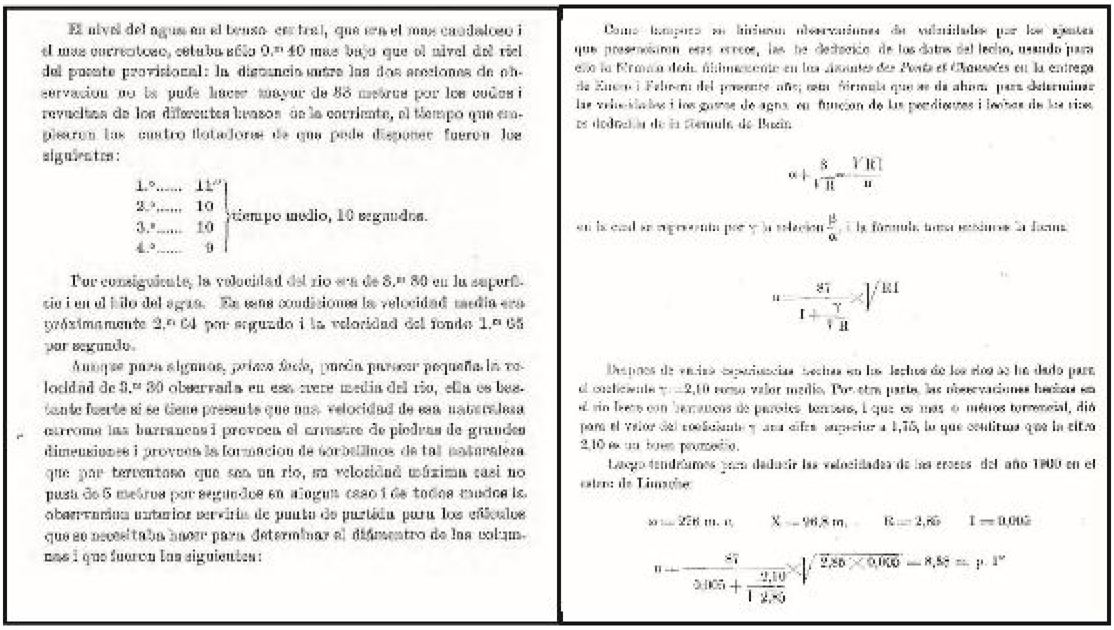

Figure 4. Extracts of Santa María's papers, with a description of surface flow velocity measurements (from Santa María, 1899b) and the application of Bazin's formula (Bazin, 1897) (from Santa María, 1909)

Critical velocities for the inception of sediment motion were observed in the field and also obtained from data by Du Buat and Telford (Du Buat, 1799), as shown in Figure 5.

ANEXO

Velocidades de arrastre dadas por las observaciones de los señores DuBuat i Telford:

	Velocidad de fondo en metro por un 1."
Tierra suelta	0.076
Arcilla parda propia para la cerámica	0.081
Arcilla blanda	0.152
Arenas depositadas por las arcillas de la cerámica	0 162
Arenas del Sena del grosor de un grano de anis	0.108
,, ,, del tamaño de una arveja	0.189
Arena corriente	0 305
Gravas del Sena	0.325
Gravas corrientes finas	0 609
Gravas de 0.025 metro de diámetro máximo	9.650
Gravas gruesas	0.914
Gravas de piedra angulosa de fusil, del tamaño de un huevo de gallina	0 975
Piedra chancada	1.220
Grava aglomerada o esquita blanda	1.520
Rocas en capas o gravas de grandes dimensiones	1.830
Rocas duras	3.950

DOMINGO V. SANTA MARÍA
Injeniero civil i de minas.

Figure 5. Appendix of Santa María's (1901a) paper with critical near bed flow velocities by Du Buat and Telford

4.2 Structure

Both scour formulas by Santa María introduced the difference between the flow and the critical flow velocity, recognizing an excess velocity as a main scour predictor, thus being much advanced than those scour formulas based on the regime theory, such as those proposed by Lacey (1929), Inglis (1949), and Blench (1962), who represented the flow effect on scour with the specific discharge and flow depth, but much more aligned with modern scour formulas such as those proposed by Jain & Fisher (1980), Melville (1997), and Sheppard et al. (2014), who recognize the importance of an excess velocity parameter for scour. Remarkably, Santa María stated that scour at bridge piers can reach up to 6-8 m under extreme flood conditions observed in Central-South Chile, an upper limit that corresponds well with the currently accepted envelope for equilibrium scour at 2.5 to 3.0 times the pier diameter. Santa María recognized the existence of a vertical velocity distribution, and thus knew that the relation between the surface and average flow velocity is not constant, varying between 0.5 and 0.8. He recommended to take a value of 0.65 for flow depths up to 10 m.

General scour was assumed by Santa María to be proportional to the square root of the excess velocity and the flow depth, while local scour at bridge piers was assumed to be proportional to the excess velocity and flow depth. As is well known today, the pier shape and, especially, its width are important factors affecting the scour depth. Santa María's scour formula did not include any pier parameter.

4.3 Performance

The local scour formula by Santa María (1901) presented in Eq. (4) was applied to three common flood situations with live bed conditions, deep water relative to pier width, and coarse sediments. Results were compared with those obtained with the scour formulas by Breusers *et al.* (1977), HEC-18 (Arneson *et al.* 2012), Sheppard *et al.* (2014), and Ettmer *et al.* (2015). Table 2 shows the variables for each case.

Table 2. Hydraulic properties defining three application cases

	Case 1	**Case 2**	**Case 3**
$\boldsymbol{u}$ **(m/s)**	2.5	4	6
$\boldsymbol{H}$ **(m)**	4	6	10
$\boldsymbol{D}$ **(m)**	0.8	1.5	1.8
$\boldsymbol{d_s}$ **(mm)**	10	20	50
$\boldsymbol{u_c}$ **(m/s)**	1.1	1.9	3.0

where D is the pier diameter and d_s is the representative sediment diameter. In the calculations the surface flow velocity in Santa María's equation was assumed equal the average flow velocity. Results are presented in the form of bar charts in Fig. 6.

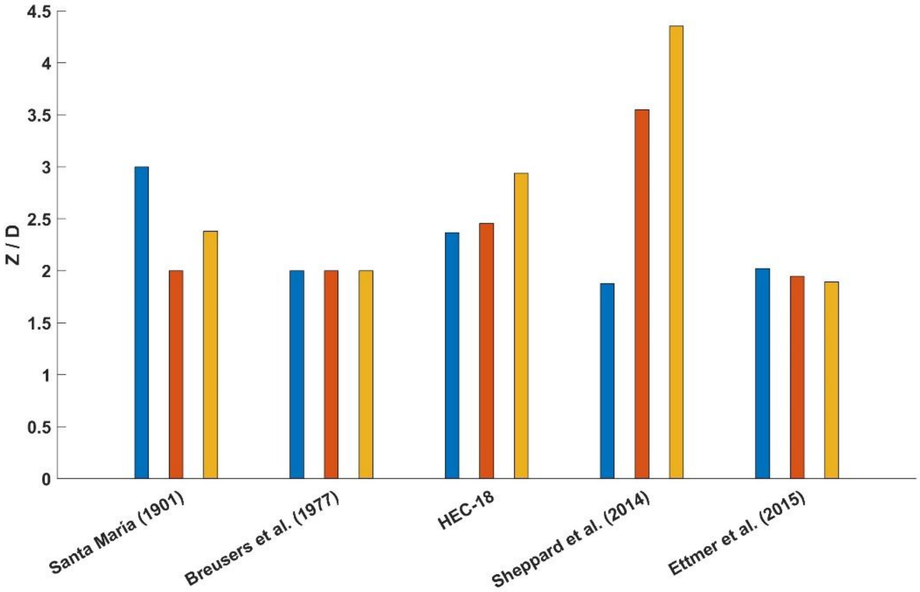

Figure 6. Comparison of normalized local scour depth predictions using the scour formulas by Santa María (1901), Breusers *et al.* (1977), HEC-18 (Arneson *et al.* 2012), Sheppard *et al.* (2014) and Ettmer *et al.* (2015) for particular live-bed scour conditions

Results obtained for the cases defined by the parameters in Table 2, Santa María's scour formula (Eq. 4) compare well with other formulas by Breusers *et al.* (1977), HEC-18 (Arneson *et al.*, 2012), Sheppard *et al.* (2014), and Ettmer *et al.* (2015).

5 Conclusion

Domingo Santa María proposed the first pier scour formulas nearly 30 years before Lacey's regime theory, and almost 50 years before Inglis published his scour formula. His equations were developed using field data from several Chilean railway bridges. They capture the main effects of the fluid, flow and sediment on scour, in line with modern formulas currently used worldwide for bridge design. Santa María introduced his scour formulas for the first time to an international audience in 1908, after having verified his findings with observations during the extreme flood of 1900. Thus, Santa María deserves full credit for having develop the first pier scour formulas.

Acknowledgements

Constanza Veloso is acknowledged for her support with geographic information systems. Daniel Hesse and Alonso Pizarro are acknowledged for their help in searching for the older literature items. Subhasish Dey is acknowledged for his feedback on the development of scour formulas in India. The author thanks the three anonymous reviewers for their constructive comments on the manuscript.

Funding

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Notation

D	=	Pier diameter (m)
d_s	=	Representative sediment particle diameter (m)
H	=	Flow depth (m)
u	=	Flow velocity (ms^{-1})
u_c	=	Critical velocity for the initiation of sediment motion (ms^{-1})
u_*	=	Near bed flow velocity (ms^{-1})
$V3$	=	Excess velocity above the incipient sediment motion condition (ms^{-1})
z	=	Scour depth (m)

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List of tables

Table 1. Bridges studied by Santa María

Nr.	Bridge	Nr.	Bridge
1	SAN FELIPE	29	MAULE
2	CURIMÓN	30	BATUCO
3	LAS OVEJAS	31	ÑUBLE
4	RABUCO	32	NEBUCO
5	LIMACHE	33	CHILLÁN
6	LOS MAQUIS	34	COYANCO
7	PASO HONDO	35	PAL PAL
8	LAS CUCHARAS	36	MONTEAGUILA
9	EL TABLÓN	37	BIOBÍO AT CERRO CHEPE
10	CHACABUCO	38	QUILACOYA
11	LAMPA	39	GOMERO
12	COLINA	40	SANTA MARÍA
13	CAL Y CANTO	41	RÍO CLARO NEAR YUMBEL
14	LA PURÍSIMA	42	LAJA
15	MAPOCHO AT SAN FRANCISCO DEL MONTE	43	PAILLIHUE
16	MAIPO	44	BIOBÍO AT COIHUE
17	DE PALOS OVER THE MAPOCHO RIVER	45	RENAICO
18	DEL LITRE	46	EL SALTO
19	QUEBRADILLA, DE PATAGUAS	47	CAUTÍN
20	ANGOSTURA	48	TOLTÉN
21	SAN FRANCISCO	49	DONGUIL
22	CACHAPOAL	50	HUEQUÉN
23	ANTIVERO	51	LEFICAHUE
24	TINGUIRIRICA	52	CIRUELOS
25	CHIMBARONGO	53	RÍO BUENO
26	TENO SUR	54	RAHUE
27	TRONCOSO	55	FORRAHUE
28	LIRCAY	56	CANCURA

Table 2. Hydraulic properties defining three application cases

	Case 1	**Case 2**	**Case 3**
U (m/s)	2.5	4	6
H (m)	4	6	10
D (m)	0.8	1.5	1.8
d_s (mm)	10	20	50
U_c (m/s)	1.1	1.9	3.0

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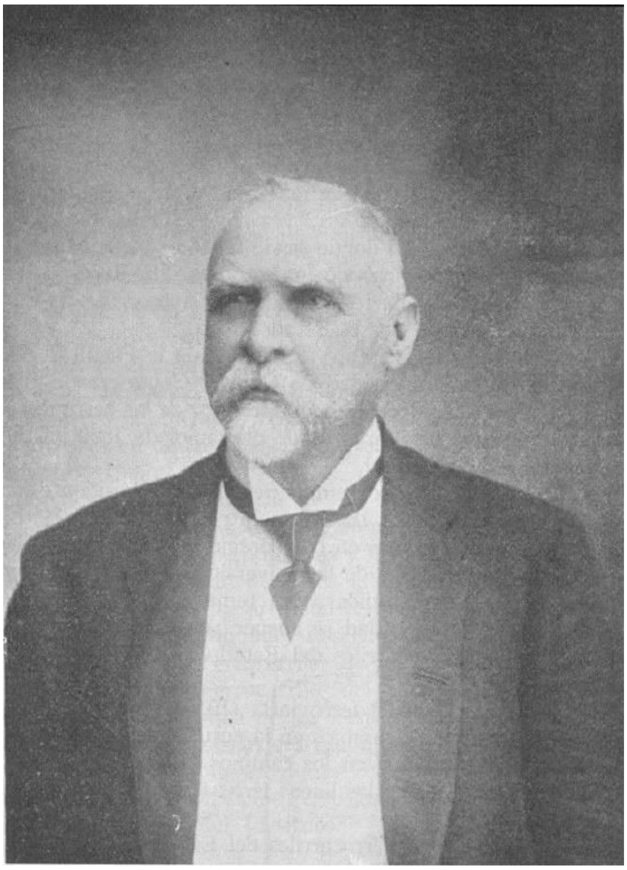


Figure 1. Domingo Víctor Santa María (1854-1919) (Source: Instituto de Ingenieros de Chile, 1919)

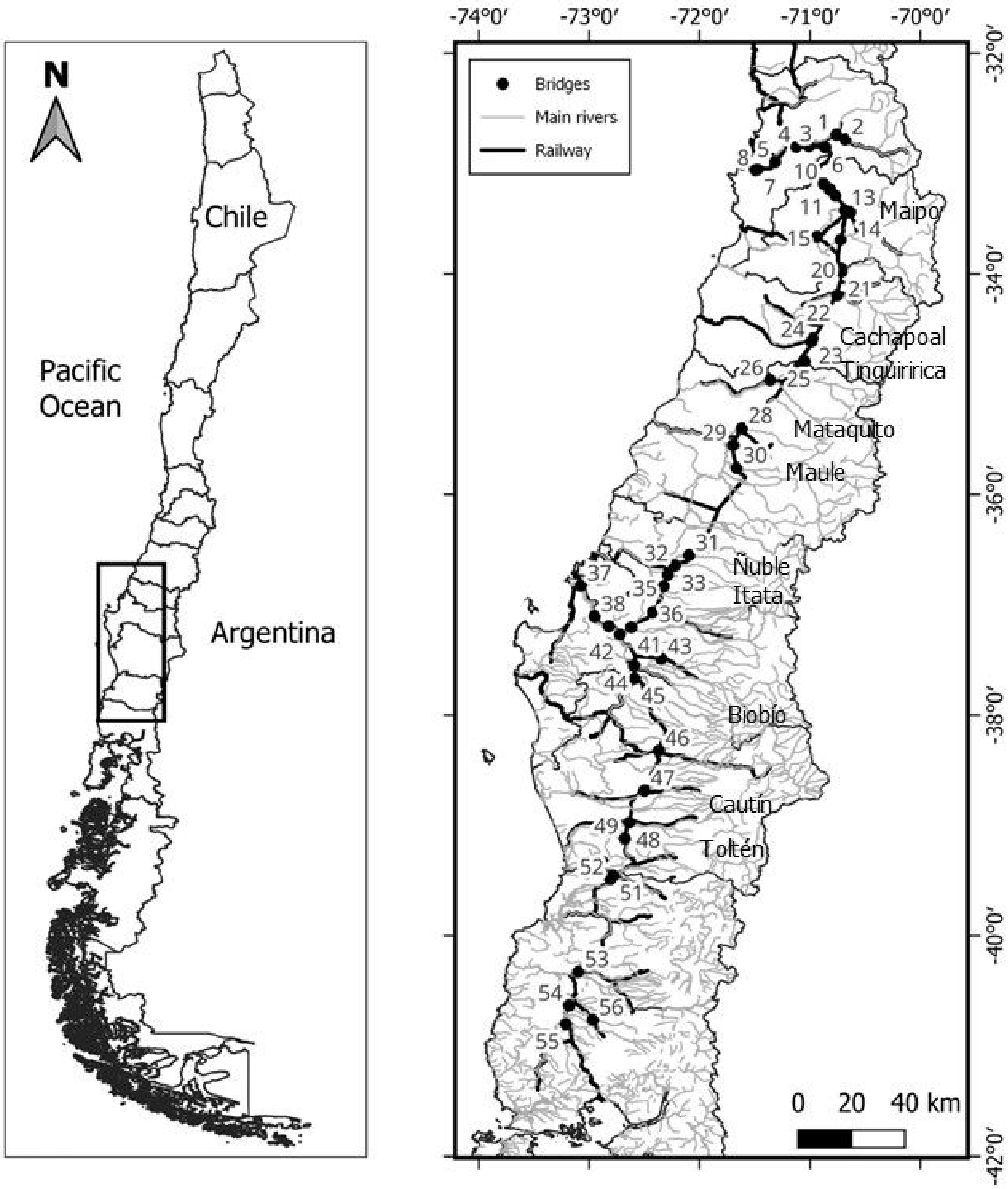


Figure 2. Location of the bridges studied by Santa María

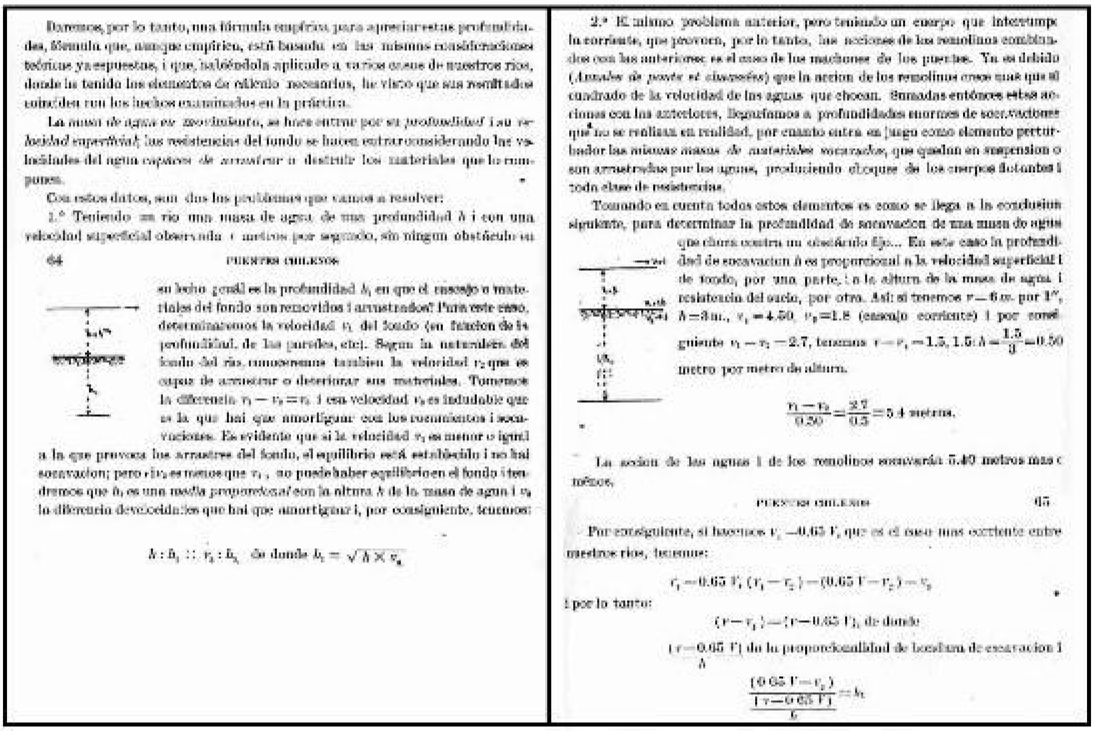
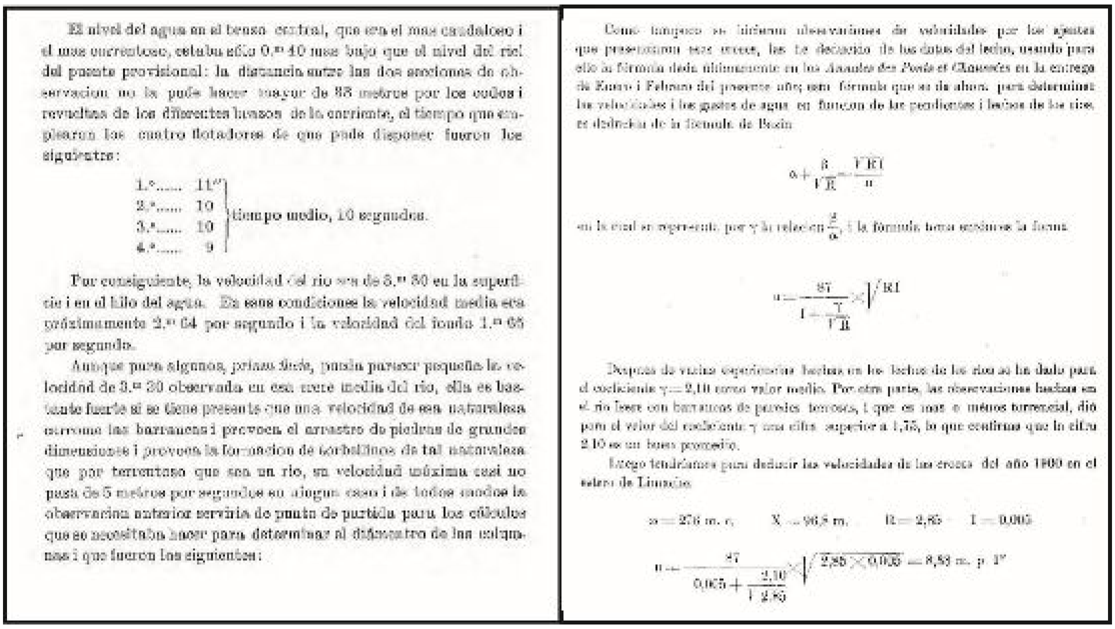


Figure 3. Derivation of scour formulas in Eqs. 1 and 2 by Santa María (1901a)



El nivel del agua en el brazo central, que era el mas caudaloso i el mas correntoso, estaba sólo 0.m 40 mas bajo que el nivel del riel del puente provisional: la distancia entre las dos secciones de observacion no la pude hacer mayor de 33 metros por los codos i revueltas de los diferentes brazos de la corriente, el tiempo que emplearon los cuatro flotadores de que pude disponer fueron los siguientes:

1.°..... 11″
2.°..... 10
3.°..... 10
4.°..... 9
tiempo medio, 10 segundos.

Por consiguiente, la velocidad del rio era de 3.m 30 en la superficie i en el hilo del agua. En esas condiciones la velocidad media era próximamente 2.m 64 por segundo i la velocidad del fondo 1.m 65 por segundo.

Aunque para algunos, prima facie, pueda parecer pequeña la velocidad de 3.m 30 observada en esa parte media del rio, ella es bastante fuerte si se tiene presente que una velocidad de esa naturaleza socava las barrancas i provoca el arrastre de piedras de grandes dimensiones i provoca la formacion de torbellinos de tal naturaleza que por torrentoso que sea un rio, su velocidad máxima casi no pasa de 5 metros por segundo en ningun caso i de todos modos la observacion anterior serviria de punto de partida para los cálculos que se necesitaba hacer para determinar el diámetro de las columnas i que fueron los siguientes:

Como tampoco se hicieron observaciones de velocidades por los ajentes que presenciaron esas creces, las he deducido de los datos del lecho, usando para ello la fórmula dada últimamente en los *Annales des Ponts et Chaussées* en la entrega de Enero i Febrero del presente año; esta fórmula que se da ahora para determinar las velocidades i los gastos de agua en funcion de las pendientes i lechos de los ríos, es deducida de la fórmula de Bazin

$$\alpha + \frac{\beta}{\sqrt{R}} = \frac{\sqrt{RI}}{u}$$

en la cual se representa por γ la relacion $\frac{\beta}{\alpha}$, i la fórmula toma entónces la forma

$$u = \frac{87}{1 + \frac{\gamma}{\sqrt{R}}} \times \sqrt{RI}$$

Despues de varias experiencias hechas en los lechos de los rios se ha dado para el coeficiente $\gamma = 2,10$ como valor medio. Por otra parte, las observaciones hechas en el rio [illegible] con barrancos de paredes terrosas, i que es mas o ménos torrencial, dió para el valor del coeficiente γ una cifra superior a 1,75, lo que confirma que la cifra 2,10 es un buen promedio.

Luego tendríamos para deducir las velocidades de las creces del año 1900 en el estero de Limache:

$$\omega = 276 \text{ m. c.} \qquad X = 96{,}5 \text{ m.} \qquad R = 2{,}85 \qquad I = 0{,}005$$

$$u = \frac{87}{0{,}065 + \frac{2{,}10}{\sqrt{2{,}85}}} \times \sqrt{2{,}85 \times 0{,}005} = 8{,}53 \text{ m. p. } 1''$$

Figure 4. Extracts of Santa María’s (1908) papers, with a description of surface flow velocity measurements (from Santa María, 1899b) and the application of Bazin’s formula (Bazin, 1897) (from Santa María, 1909)

ANEXO

Velocidades de arrastre dadas por las observaciones de los señores DuBuat i Telford:

	Velocidad de fondo en metro por un 1."
Tierra suelta	0.076
Arcilla parda propia para la cerámica	0.081
Arcilla blanda	0.152
Arenas depositadas por las arcillas de la cerámica	0 162
Arenas del Sena del grosor de un grano de anis	0.108
,, ,, del tamaño de una arveja	0.189
Arena corriente	0 305
Gravas del Sena	0.325
Gravas corrientes finas	0 609
Gravas de 0.025 metro de diámetro máximo	9.650
Gravas gruesas	0.914
Gravas de piedra angulosa de fusil, del tamaño de un huevo de gallina	0.975
Piedra chancada	1.220
Grava aglomerada o esquita blanda	1.520
Rocas en capas o gravas de grandes dimensiones	1.830
Rocas duras	3.950

DOMINGO V. SANTA MARÍA
Injeniero civil i de minas.

Figure 5. Appendix of Santa María's (1901a) paper with observed critical near bed flow velocities by Du Buat (1799) and Telford

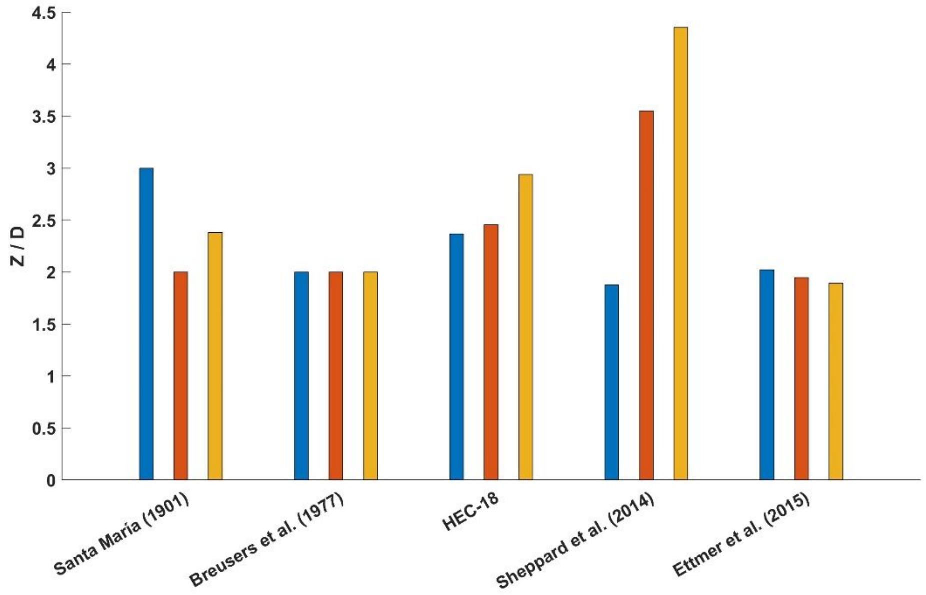


Figure 6. Comparison of normalized local scour depth predictions using the scour formulas by Santa María (1901), Breusers *et al.* (1977), HEC-18 (Arneson *et al.* 2012), Sheppard *et al.* (2014) and Ettmer *et al.* (2015) for particular live-bed scour conditions

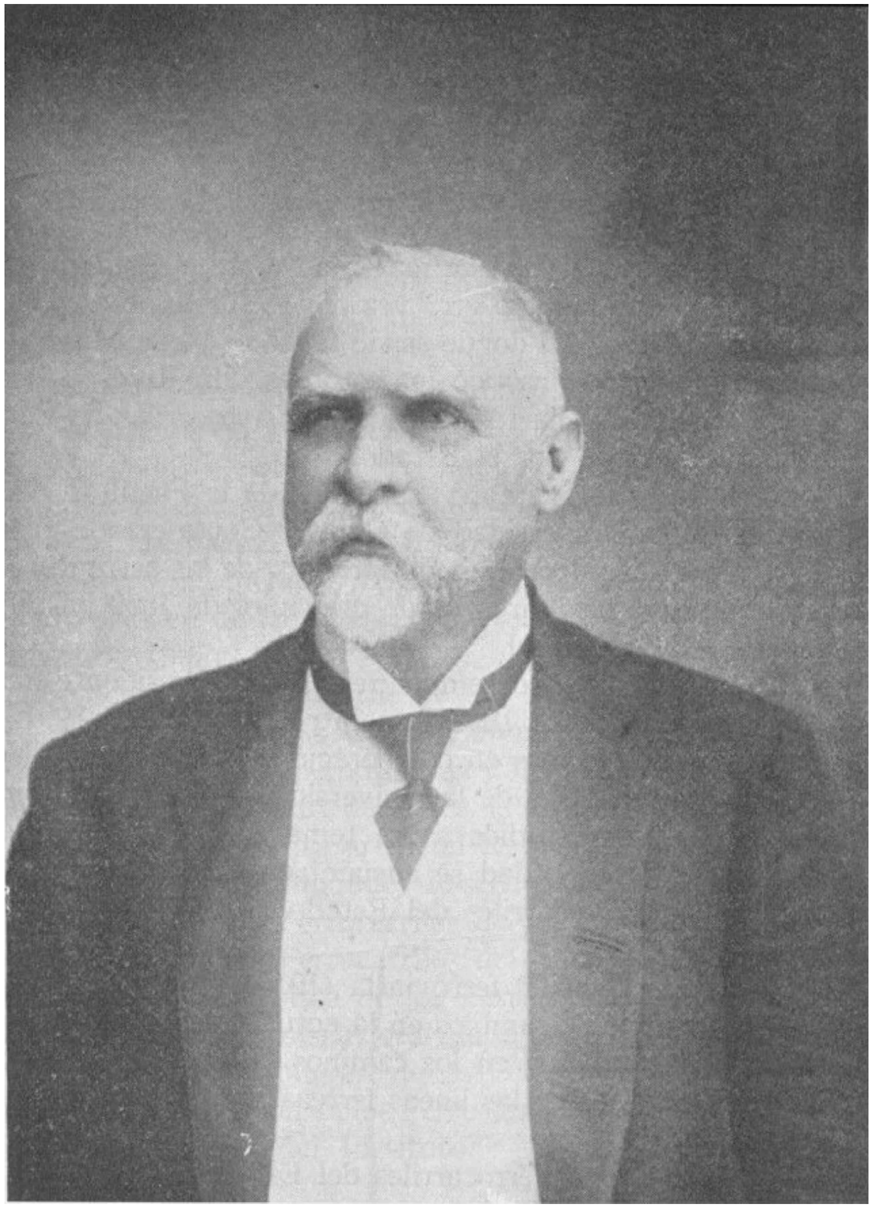


Figure 1. Domingo Víctor Santa María (1854-1919)

203x281mm (400 x 400 DPI)

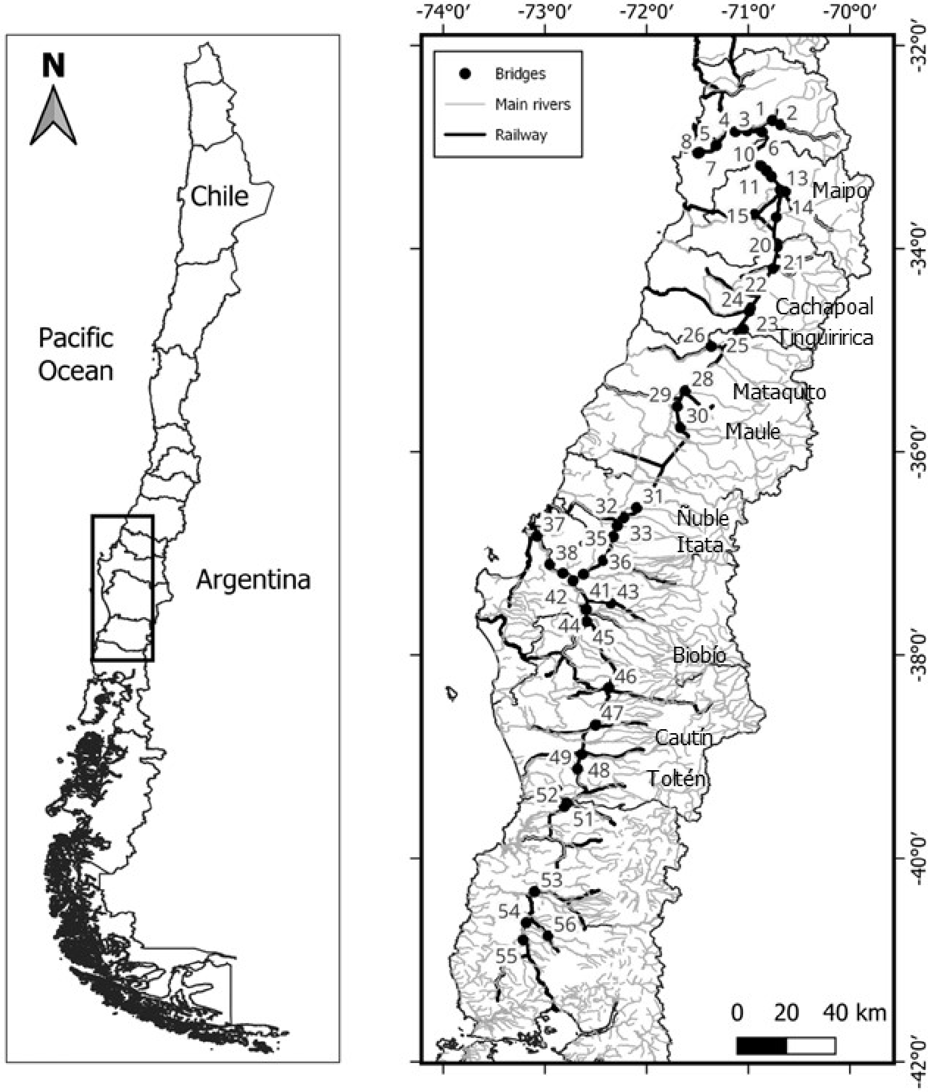
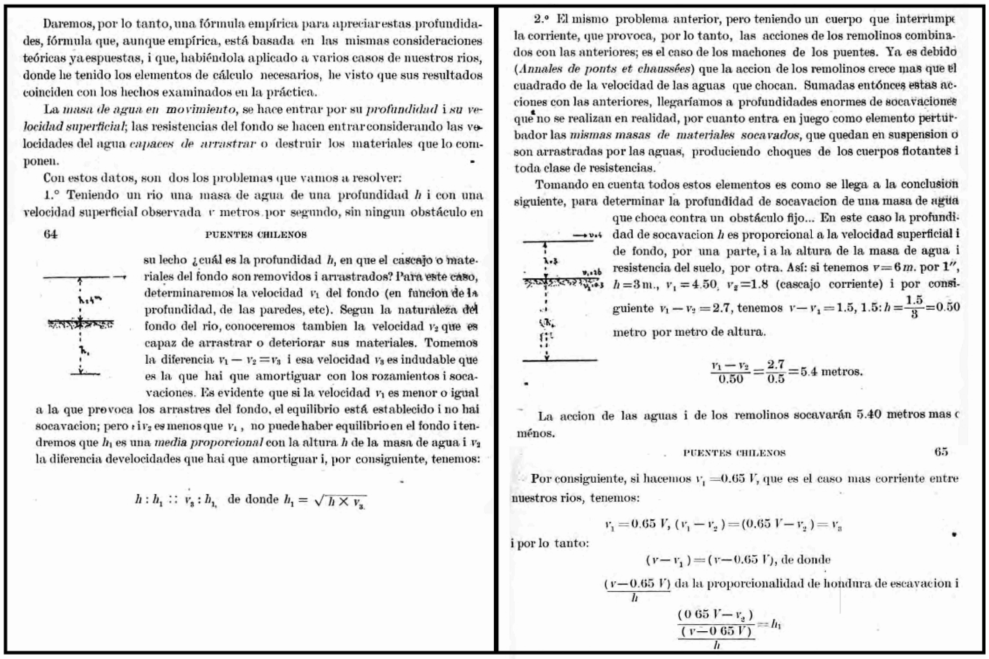


Figure 2. Location of the bridges studied by Santa María

179x200mm (96 x 96 DPI)



Daremos, por lo tanto, una fórmula empírica para apreciar estas profundidades, fórmula que, aunque empírica, está basada en las mismas consideraciones teóricas ya espuestas, i que, habiéndola aplicado a varios casos de nuestros rios, donde he tenido los elementos de cálculo necesarios, he visto que sus resultados coinciden con los hechos examinados en la práctica.

La *masa de agua en movimiento*, se hace entrar por su *profundidad* i *su velocidad superficial*; las resistencias del fondo se hacen entrar considerando las velocidades del agua *capaces de arrastrar* o destruir los materiales que lo componen.

Con estos datos, son dos los problemas que vamos a resolver:

1.° Teniendo un rio una masa de agua de una profundidad h i con una velocidad superficial observada v metros por segundo, sin ningun obstáculo en

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su lecho ¿cuál es la profundidad h, en que el cascajo o materiales del fondo son removidos i arrastrados? Para este caso, determinaremos la velocidad v_1 del fondo (en funcion de la profundidad, de las paredes, etc). Segun la naturaleza del fondo del rio, conoceremos tambien la velocidad v_2 que es capaz de arrastrar o deteriorar sus materiales. Tomemos la diferencia $v_1 - v_2 = v_3$ i esa velocidad v_3 es indudable que es la que hai que amortiguar con los rozamientos i socavaciones. Es evidente que si la velocidad v_1 es menor o igual a la que provoca los arrastres del fondo, el equilibrio está establecido i no hai socavacion; pero si v_2 es menos que v_1, no puede haber equilibrio en el fondo i tendremos que h_1 es una *media proporcional* con la altura h de la masa de agua i v_2 la diferencia develocidades que hai que amortiguar i, por consiguiente, tenemos:

$$h : h_1 :: v_3 : h_1, \text{ de donde } h_1 = \sqrt{h \times v_3}$$

2.° El mismo problema anterior, pero teniendo un cuerpo que interrumpe la corriente, que provoca, por lo tanto, las acciones de los remolinos combinados con las anteriores; es el caso de los machones de los puentes. Ya es debido (*Annales de ponts et chaussées*) que la accion de los remolinos crece mas que el cuadrado de la velocidad de las aguas que chocan. Sumadas entónces estas acciones con las anteriores, llegaríamos a profundidades enormes de socavaciones que no se realizan en realidad, por cuanto entra en juego como elemento perturbador las *mismas masas de materiales socavados*, que quedan en suspension o son arrastradas por las aguas, produciendo choques de los cuerpos flotantes i toda clase de resistencias.

Tomando en cuenta todos estos elementos es como se llega a la conclusion siguiente, para determinar la profundidad de socavacion de una masa de agua que choca contra un obstáculo fijo... En este caso la profundidad de socavacion h es proporcional a la velocidad superficial i de fondo, por una parte, i a la altura de la masa de agua i resistencia del suelo, por otra. Así: si tenemos $v = 6\,m.$ por 1″, $h = 3$ m., $v_1 = 4.50$, $v_2 = 1.8$ (cascajo corriente) i por consiguiente $v_1 - v_2 = 2.7$, tenemos $v - v_1 = 1.5$, $1.5 : h = \frac{1.5}{3} = 0.50$ metro por metro de altura.

$$\frac{v_1 - v_2}{0.50} = \frac{2.7}{0.5} = 5.4 \text{ metros.}$$

La accion de las aguas i de los remolinos socavarán 5.40 metros mas o ménos.

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Por consiguiente, si hacemos $v_1 = 0.65\,V$, que es el caso mas corriente entre nuestros rios, tenemos:

$$v_1 = 0.65\,V,\ (v_1 - v_2) = (0.65\,V - v_2) = v_3$$

i por lo tanto:

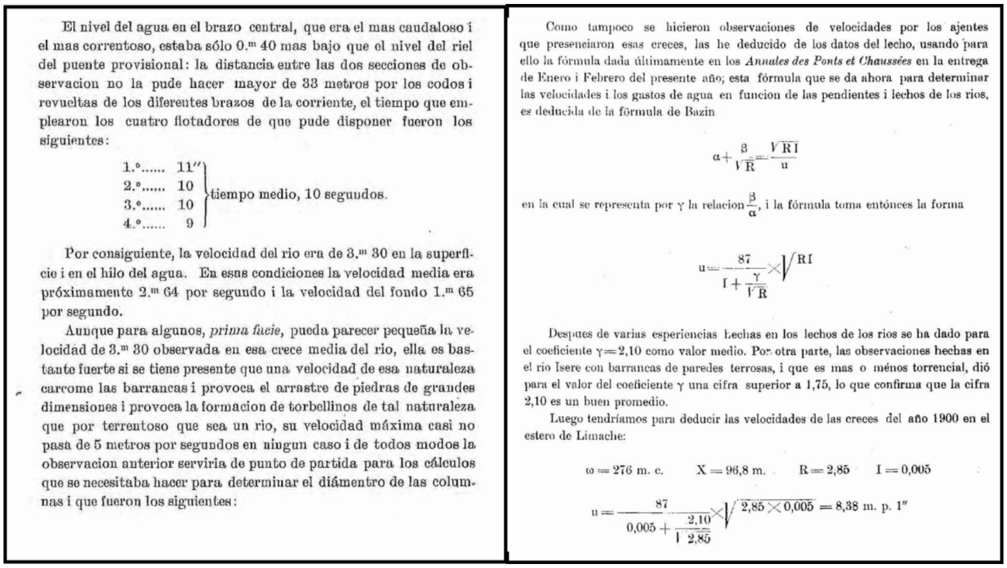
$$(v - v_1) = (v - 0.65\,V), \text{ de donde}$$

$\frac{(v - 0.65\,V)}{h}$ da la proporcionalidad de hondura de escavacion i

$$\frac{(0\,65\,V - v_2)}{\frac{(v - 0\,65\,V)}{h}} = h_1$$

Figure 3. Derivation of scour formulas in Eqs. 1 and 2 by Santa María (1901a)

442x298mm (400 x 400 DPI)



El nivel del agua en el brazo central, que era el mas caudaloso i el mas correntoso, estaba sólo 0.^{m} 40 mas bajo que el nivel del riel del puente provisional: la distancia entre las dos secciones de observacion no la pude hacer mayor de 33 metros por los codos i revueltas de los diferentes brazos de la corriente, el tiempo que emplearon los cuatro flotadores de que pude disponer fueron los siguientes:

$$\left.\begin{array}{ll} 1.^{o}\ldots\ldots & 11'' \\ 2.^{o}\ldots\ldots & 10 \\ 3.^{o}\ldots\ldots & 10 \\ 4.^{o}\ldots\ldots & 9 \end{array}\right\}\text{tiempo medio, 10 segundos.}$$

Por consiguiente, la velocidad del rio era de 3.^{m} 30 en la superficie i en el hilo del agua. En esas condiciones la velocidad media era próximamente 2.^{m} 64 por segundo i la velocidad del fondo 1.^{m} 65 por segundo.

Aunque para algunos, *prima facie*, pueda parecer pequeña la velocidad de 3.^{m} 30 observada en esa crece media del rio, ella es bastante fuerte si se tiene presente que una velocidad de esa naturaleza carcome las barrancas i provoca el arrastre de piedras de grandes dimensiones i provoca la formacion de torbellinos de tal naturaleza que por terrentoso que sea un rio, su velocidad máxima casi no pasa de 5 metros por segundos en ningun caso i de todos modos la observacion anterior serviria de punto de partida para los cálculos que se necesitaba hacer para determinar el diámentro de las columnas i que fueron los siguientes:

Como tampoco se hicieron observaciones de velocidades por los ajentes que presenciaron esas creces, las he deducido de los datos del lecho, usando para ello la fórmula dada últimamente en los *Annales des Ponts et Chaussées* en la entrega de Enero i Febrero del presente año; esta fórmula que se da ahora para determinar las velocidades i los gastos de agua en funcion de las pendientes i lechos de los rios, es deducida de la förmula de Bazin

$$\alpha + \frac{\beta}{\sqrt{R}} = \frac{\sqrt{RI}}{u}$$

en la cual se representa por γ la relacion $\frac{\beta}{\alpha}$, i la fórmula toma entónces la forma

$$u = \frac{87}{I + \frac{\gamma}{\sqrt{R}}} \times \sqrt{RI}$$

Despues de varias esperiencias hechas en los lechos de los rios se ha dado para el coeficiente $\gamma = 2,10$ como valor medio. Por otra parte, las observaciones hechas en el rio Isere con barrancas de paredes terrosas, i que es mas o ménos torrencial, dió para el valor del coeficiente γ una cifra superior a 1,75, lo que confirma que la cifra 2,10 es un buen promedio.

Luego tendríamos para deducir las velocidades de las creces del año 1900 en el estero de Limache:

$$\omega = 276 \text{ m. c.} \qquad X = 96,8 \text{ m.} \qquad R = 2,85 \qquad I = 0,005$$

$$u = \frac{87}{0,005 + \frac{2,10}{\sqrt{2,85}}} \times \sqrt{2,85 \times 0,005} = 8,38 \text{ m. p. } 1''$$

Figure 3. Extracts of Santa María (1908) paper, with a description of surface flow velocity measurements and the application of Bazin's formula

435x243mm (400 x 400 DPI)

ANEXO

Velocidades de arrastre dadas por las observaciones de los señores DuBuat i Telford:

	Velocidad de fondo en metro por un 1."
Tierra suelta	0.076
Arcilla parda propia para la cerámica	0.081
Arcilla blanda	0.152
Arenas depositadas por las arcillas de la cerámica	0 162
Arenas del Sena del grosor de un grano de anis	0.108
,, ,, del tamaño de una arveja	0.189
Arena corriente	0 305
Gravas del Sena	0.325
Gravas corrientes finas	0 609
Gravas de 0.025 metro de diámetro máximo	9.650
Gravas gruesas	0.914
Gravas de piedra angulosa de fusil, del tamaño de un huevo de gallina	0 975
Piedra chancada	1.220
Grava aglomerada o esquita blanda	1.520
Rocas en capas o gravas de grandes dimensiones	1.830
Rocas duras	3.950

Domingo V. Santa María
Injeniero civil i de minas.

Figure 4. Appendix of Santa María's (1901) paper with critical near bed flow velocities by Du Buat and Telford

211x200mm (400 x 400 DPI)

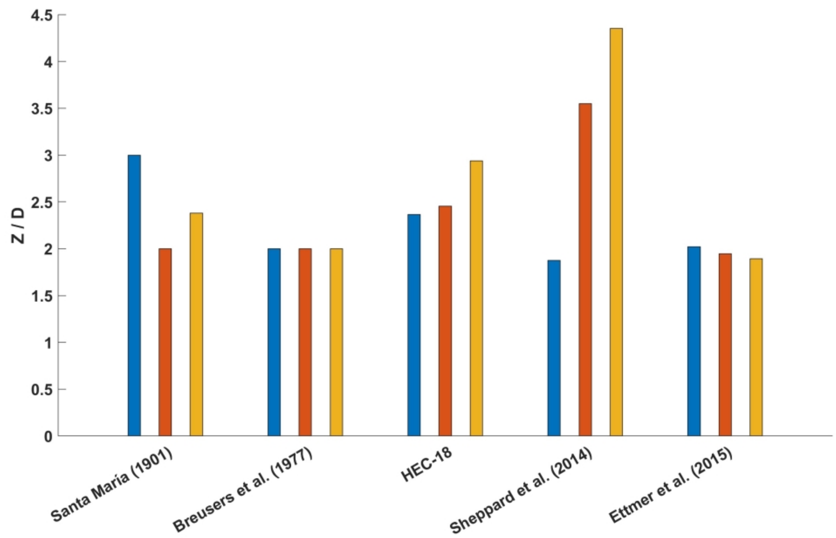


Figure 6. Comparison of normalized local scour depth predictions using the scour formulas by Santa María (1901), Breusers et al. (1977), HEC-18 (Arneson et al. 2012), Sheppard et al. (2014) and Ettmer et al. (2015) for particular live-bed scour conditions

1058x600mm (72 x 72 DPI)

Appendix

Translation of Figure 3. Derivation of scour formulas in Eqs. (2) and (4) by Santa María (1901a)

We will provide, therefore, an empirical formula for estimation of these scour depths, a formula which, although empirical, is based on the same theoretical considerations already exposed, and which, having applied it to several cases of our rivers, where I have had the necessary elements of calculation, I have seen that its results coincide with the facts examined in practice.

The mass of water in motion is considered in the formula by its depth and its velocity, while the bottom resistances are considered through the water velocities capable of dragging or destroying the bed materials.

It is evident that if the velocity *V1* is less than or equal to that which causes the sediment motion, equilibrium is established and there is no scour; but if *V2* is less than *V1*, there can be no equilibrium at the bottom and we will have that *h1* is an average proportional with the height *h* of the water mass and *V2* is the difference of velocities to be damped and, consequently, we have:

h : *h1* :: *V3* : *h1* and thus $\mathrm{h1} = \sqrt{h * V3}$

2) The same problem as above, but having a body that interrupts the current, which causes, therefore, the actions of the eddies combined with the previous ones; it is the case of the bridge piers and abutments. It is already believed (*Annales de ponts et chaussées*) that the action of the eddies grows more than the square of the speed of the colliding waters. Adding then these actions with the previous ones, we would arrive at enormous scour depths that are not observed in reality, because the same masses of scoured materials come into play as a disturbing element, which remain in suspension or are dragged by the waters, producing collisions of the floating bodies and all kinds of resistances.

Taking all these elements into account, the following conclusion can be reached to determine the scour depth caused by a mass of water that collides with a fixed obstacle. In this case the scour depth is proportional to the surface flow velocity and the near bed flow velocity, on the one hand, and to the depth of the water mass and soil resistance, on the other hand. Thus, if we have *v* = 6 ms-1, *h* = 3 m, *V1* = 4 .50. *V2* = 1.8 ms-1 (running gravel) and therefore *V2* - *V1* = 2.7, we have *v* - *V1* = 1.5, 1.5: *h* =1.5 / 3 = 0.50 meter per meter of height

$$\frac{V1 - V2}{0.5} = \frac{2.7}{0.5} = 5.4 \text{ m}$$

The action of the eddy waters will undermine 5.40 meters more or less.

Therefore, if we make $V1 = 0.65\ V$, which is the most common case among our rivers, we have:

$$V1 = 0.65\ V, (V1 - V2) = V3$$

and thus,

$$(V1 - V2) = (V - 0.65V), \text{ from which}$$

$$V1 = 0.65\ V, \text{ from which}$$

$$\frac{V - 0.65V}{h} \text{ gives the proportionality for de scour depth:}$$

$$\frac{(0.65V - V2)}{\frac{(V - 0.65V)}{h}} = h1$$

Translation of Figure 4. Extracts of Santa María's papers, with a description of surface flow velocity measurements (from Santa María, 1899b) and the application of Bazin's formula (Bazin, 1897) (from Santa María, 1909)

The water level in the central arm, which was the most abundant and the most was only 0.40 m lower than the level of the rail of the provisional bridge: the distance between the two observation sections could not be more than 33 meters because of the bends of the different branches of the stream, the time spent by the four available floats were as follows:

1.°...... 11''
2.°...... 10
3.°...... 10
4.°...... 9

average time in seconds

Consequently, the velocity of the river was 3.30 ms-1 at the surface

and in the water body. Under these conditions the average velocity was approximately 2.04 ms-1 and the near bed velocity 1.65 ms-1.

As no observations of velocities were made either by the people who witnessed these floods, I have deduced them from the bed data, using for this purpose the formula recently given in the Annales des Ponts et Chaussées in the January and February issue of the present year; the formulas given tin the following for the calculation of the velocities and water discharges as a function of the slopes and beds of the rivers, is deduced from Bazin's formula:

$$\alpha + \frac{\beta}{\sqrt{R}} = \frac{\sqrt{RI}}{u}$$

in which the beta / alpha ratio is represented by gamma and the formula then takes the form

$$u = \frac{87}{I + \frac{\gamma}{\sqrt{R}}} \times \sqrt{RI}$$

After several experiments made in river beds, a mean value of 2.10 has been given for the gamma coefficient. On the other hand, the observations made on the Isere river, which is more or less torrential, with its earthy walled ravines, gave for the gamma coefficient a value higher than 1.75, which confirms that 2.1 is a good average.

Then we would have to deduce the velocities of the 1900 floods in the Limache stream:

$\omega = 276$ m. c. $\quad X = 96{,}8$ m. $\quad R = 2{;}85 \quad I = 0{,}005$

$$u = \frac{87}{0{,}005 + \frac{2{,}10}{\sqrt{2{,}85}}} \times \sqrt{2{,}85 \times 0{,}005} = 8{,}38 \text{ m. p. } 1''$$

Santa María and the first pier scour formulas

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ABSTRACT

Domingo Santa María was the first to present pier scour formulas, one for the estimation of general scour ~~erosion~~ or bed degraddation in rivers and another one for the estimation of maximum local scour depth at a bridge pier. His analysis was based on field observations ~~of~~ at 56 bridges crossing Chilean rivers, with especial attention to the behaviour of railway bridges under conditions imposed by extreme floods. ~~-~~Santa María dedicated almost 20 years to the public service and another 20 years to the academy. Among several different tasks for the Chilean governments and the Ministry of Public Works, he was in charge of planning and supervising the construction of the main railway, connecting Santiago with the southern part of the country over ca. 1000 km. In the present paper, the pioneer scour formulas by Santa María are analysed and compared with other, well established scour formulas to highlight Santa María's outstanding contribution to the development of hydraulic engineering.

Keywords: Biography, bridges, history, hydraulics, scour, ~~history, hydraulics,~~ sediment, water.~~, bridges.~~

1 Introduction

Scour at bridge elements is one of the most complex, fascinating and researched topics in hydraulics, first started by Durand-Claye (1873) and Engels (1894) through exploratory flume experiments that provided evidence to solve very basic and practical engineering questions such as: what pier shape is more favourable to prevent scour: rectangular, round nosed, lenticular, ogival, etc?, or, important for scour protection: where does the maximum scour depth around a bridge pier occur: at the pier front, at the sides, or at the pier back? A 25-years long gap of studies on the bridge pier scour is detected between 1895 and 1920. Presumably, scholars were dedicated to study the flow at piers with focus on the backwater effects for navigation. Studies and analysis of scour for specific bridges were published by Rehbock (1921) on the German river Wiesent near the city of Nürnberg, and by Yarnell and Nagler (1931) on the North Carolina standard reinforced concrete bridge pier. Keutner (1932), Tison (1940), Ishihara (1942), Chabert and Engeldinger (1956), as well as Laursen and Toch (1956) published detailed characterizations of scour hole geometry for a number of different experimental conditions, and were able to identify effects of flow velocity, flow attack angle, flow depth, sediment size, pier shape and pier length on scour. Laursen and Toch (1956) stated: "Neither these early experiments nor subsequent studies by various investigators in various countries have been sufficiently general to obtain the desired result – a means of predicting scour in the field." The oldest scour formula present~~inform~~ed in the famous state of the art paper by Breusers *et al.* (1977) as well as compared by Sheppard et al. (2014) is that by Sir C. Inglis (1944, 1949), which is based on Lacey's method (Lacey, 1929) of estimating regime depth of flow in loose bed alluvial rivers (Kothyari, 2008), and field data ~~from~~ of 17 bridges in India and Pakistan ~~that were~~ collected between 1924 and 1942.

Nearly a century before Inglis (1949) published his bridge pier scour formula, the golden age of rail started, promoted by the industrial revolution. In the second half of the XIX century the Chilean economy boomed thanks to the saltpeter export and thus the country was able to put forward the development of the national railways for the transportation of minerals to the ports at the Pacific Ocean, and to achieve the connectivity of the main city of Santiago with the northern part of the country, and with the far South (Oppenheimer, 1982). As the main Chilean longitudinal railway along the Central Valley crosses important rivers that flow from the Andes to the Pacific Ocean, the construction of bridges was especially relevant to achieve the connectivity goal. In doing so, several national e.g.: Juan Slater Co., Albarracín y Urrutia Co., as well as foreign, international companies were asked by the Chilean governments to build different railways, e.g.: Manby & Co built the Arauco Railway and Biobío bridge at Concepción (Manby, 1892), The North and South American Construction Company from New York built ten new railroads totalizing 1175 km (Edwards, 2001). Main d-ifficulties for achieving the construction of the railways and particularly, their bridges is related to the fact that no electricity was available neither automobiles for transport of materials. Especially challenging was the construction of bridges foundations by means of screw-piles, small hydraulic-jet, or concrete piers in wrought-iron cylinders sunk by machine diggers.

The Chilean engineer Domingo Santa María was in charge for the planning, supervision, construction and maintenance of several railways and bridges built by the end of the XIX century. He dedicated especial attention to the design of the railway bridges located in Central-South Chile. As in this zone floods are frequent and severe, ~~so did~~ many bridges partially collapse during construction or shortly thereafter. Santa María was concerned about scour as one of the main causes of bridge collapses. In a first communication, Santa María (1901a,b,c,d) presented his empirical formulas as part of an analysis of scour at 56 different bridges under conditions imposed by extreme floods such as those occurring~~ed~~ in 1877, and 1888. After an extended analysis of scour at bridges considering the extreme flood occurred in 1900, Santa María proposed his scour formulas in 1908 at the fourth Latin-American and first Pan-American Scientific Congress, held in Santiago de Chile ~~between December 25th, 1908 and January 6th, 1909~~ (Holmes, 1909).

In this paper, the ideas and work of the Chilean engineer, Domingo Santa María (1854-1919) are revis~~present~~ed. The next section presents ~~the~~ a brief biography of Santa María, who developed his career after graduating as Geographic Engineer in 1874 and as

Mining Engineer in 1875, both at Universidad de Chile, and as Civil Engineer in 1878 at the University of Ghent. Thereafter, the main ideas and works on scour by Santa María are revised, including the development of the first bridge scour formulas. Next, Santa María's formula for estimating~~on~~ the ~~of~~ maximum scour depth at bridge piers is analysed and compared with modern formulas.

2 Brief biography of Domingo Víctor Santa María

Domingo Víctor Santa María Márquez de la Plata was born on March~~,~~ 6th, 1854, at Santiago de Chile. His father, Domingo Santa María, was an outstanding Chilean politician, who was president in the period 1881-1886. At the age of 20 years, Santa María graduated as Geography Engineer at Universidad de Chile, and one year later he graduated as Mining Engineer at the same university. Thereafter he moved to Belgium, where he graduated as Civil Engineer in 1878 from~~at~~ the University of Ghent (note that ~~t~~its~~he~~ Hydraulics Laboratory ~~at Ghent University~~ was founded in 1935 by Prof L.J. Tison). Back from Europe, Santa María worked as professional engineer in several railways, ports and bridges projects for the Chilean government, and in parallel started a political career, being member of the House of Representatives in two consecutive periods, 1879-1884 and 1885-1888.

~~In 1888, h~~He was General Director of Public Works in 1888~~for one year~~, after which he ~~moved to a~~become technical inspector ~~position~~ in charge of the acquisition of trains for the Chilean state. For this purpose, he lived for two years in Europe. Back in Chile again, ~~in 1891~~ he assumed in 1891 a second period as General Director of Public Works, until May 14th, 1895 (Instituto de Ingenieros, 1919).

Santa María was a faculty member at Universidad de Chile between 1899 and 1919. He teached the courses “bridges” and “railways”, and was dean of the Faculty of Physical and Mathematical Sciences between 1907-1909. As a prolific scholar, Santa María published over 40 communications in the Anales de la Universidad de Chile and the Anales del Instituto de Ingenieros de Chile (https://revistas.uchile.cl/index.php/AICH/issue/archive) on diverse engineering topics, such as planning of railways, the use of mild steel in railway bridges, debris flows, scour at bridge elements, and the supply of the drinking water in cities.

Santa María passed away on~~over in~~ December 11th, 1919, at the age of 65 years.

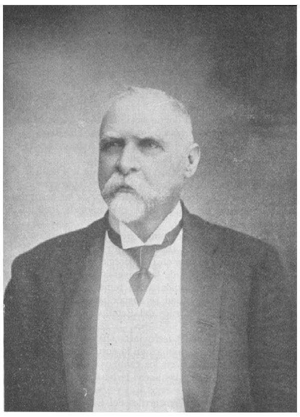


Figure 1. Domingo Víctor Santa María (1854-1919) (Source: Instituto de Ingenieros de Chile, 1919)

3 The scour formula by Santa María

3.1 The 1901 paper

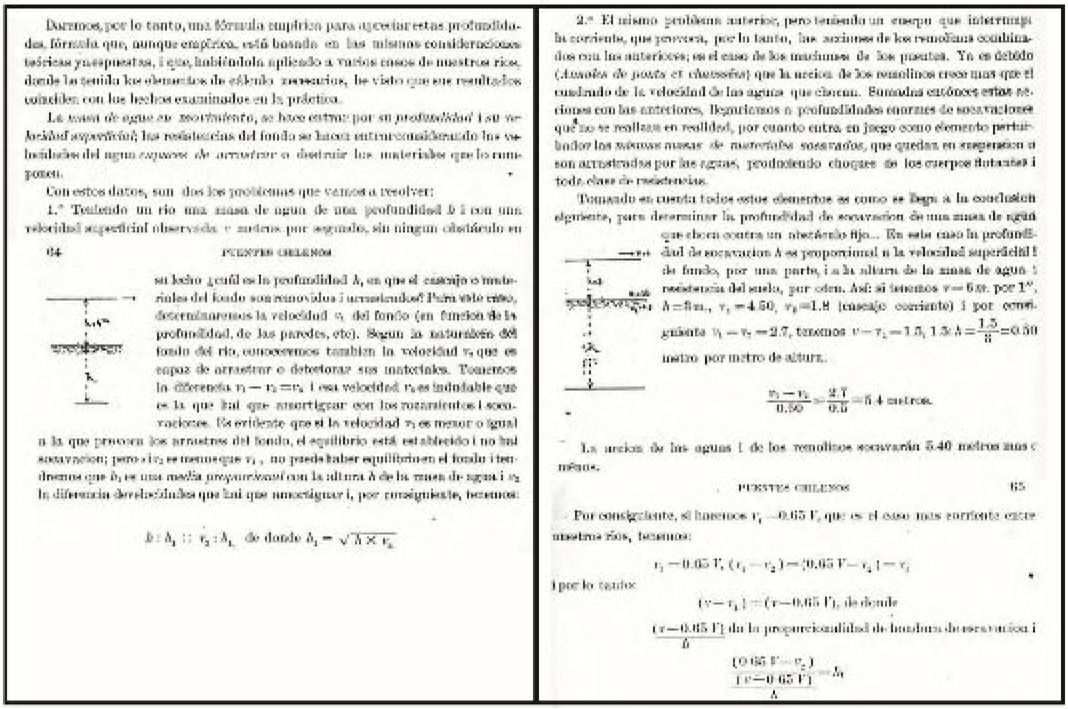
~~Entitled "Puentes Chilenos" (Chilean bridges), in this communication~~ In a series of four parts (Santa María, 1901a, 1901b, 1901c, and 1901d) entitled "Puentes Chilenos" (Chilean bridges), Santa María exposed observations on the behaviour of different rivers located in Central-South Chile, providing pertinent recommendations to practical engineers with special focus on the foundations. After an introduction in Chapter I, Chapter II ~~is dedicated to provide a description of~~describe the ~~behavior~~behaviour of mountain rivers ~~behaviour~~ based on observations of Chilean rivers located between rivers Maipo and Toltén. Chapter III presents a formula for general scour~~erosion~~, ~~which he proposes to be proportional to the flow depth as well as to the at the riverbed near-bed excess flow velocity at the riverbed:~~

$$\cancel{z_{max} = \sqrt{H(u_* - u_{*,cr})}}$$

~~and a formula for estimation of the scour depth at a bridge pier:~~

$$\cancel{z_{max} = H\frac{(u_* - u_{*,cr})}{(U - u_*)}}$$

~~where z_{max} is the maximum scour depth, H is the flow depth, U is the average flow velocity, u_* is the flow velocity at the riverbed, and $u_{*,cr}$ is the critical flow velocity at the riverbed for incipient sediment motion. Figure 2 shows the derivation of both scour equations by Santa María (1901).~~



Darémos, por lo tanto, una fórmula empírica para apreciar estas profundidades, fórmula que, aunque empírica, está basada en las mismas consideraciones teóricas ya espuestas, i que, habiéndola aplicado a varios casos de nuestros ríos, donde he tenido los elementos de cálculo necesarios, he visto que sus resultados coinciden con los hechos examinados en la práctica.

La *masa de agua en movimiento*, se hace entrar por su *profundidad* i su *velocidad superficial*; las resistencias del fondo se hacen entrar considerando las velocidades del agua *capaces de arrastrar* o destruir los materiales que lo componen.

Con estos datos, son dos los problemas que vamos a resolver:

1.° Teniendo un río una masa de agua de una profundidad h i con una velocidad superficial observada v metros por segundo, sin ningun obstáculo en

64 PUENTES CHILENOS

su lecho ¿cuál es la profundidad h_1 en que el cascajo o materiales del fondo son removidos i arrastrados? Para este caso, determinaremos la velocidad v_1 del fondo (en funcion de la profundidad, de las paredes, etc). Segun la naturaleza del fondo del río, conoceremos tambien la velocidad v_2 que es capaz de arrastrar o deteriorar sus materiales. Tomemos la diferencia $v_1 - v_2 = v_3$ i esa velocidad v_3 es indudable que es la que hai que amortiguar con los rozamientos i socavaciones. Es evidente que si la velocidad v_1 es menor o igual a la que provoca los arrastres del fondo, el equilibrio está establecido i no hai socavacion; pero si v_2 es menor que v_1, no puede haber equilibrio en el fondo i tendremos que h_1 es una *media proporcional* con la altura h de la masa de agua i v_3 la diferencia de velocidades que hai que amortiguar i, por consiguiente, tenemos:

$$h : h_1 :: v_3 : h_1 \quad \text{de donde} \quad h_1 = \sqrt{h \times v_3}$$

2.° El mismo problema anterior, pero teniendo un cuerpo que interrumpa la corriente, que provoca, por lo tanto, las acciones de los remolinos combinados con las anteriores; es el caso de los machones de los puentes. Ya es debido (*Annales des ponts et chaussées*) que la accion de los remolinos crece mas que el cuadrado de la velocidad de las aguas que chocan. Sumadas entónces estas acciones con las anteriores, llegaríamos a profundidades enormes de socavaciones que no se realizan en realidad, por cuanto entra en juego como elemento perturbador las *mismas masas de materiales socavados*, que quedan en suspension o son arrastradas por las aguas, produciendo choques de los cuerpos flotantes i toda clase de resistencias.

Tomando en cuenta todos estos elementos es como se llega a la conclusion siguiente, para determinar la profundidad de socavacion de una masa de agua que choca contra un obstáculo fijo... En este caso la profundidad de socavacion h es proporcional a la velocidad superficial i de fondo, por una parte, i a la altura de la masa de agua i resistencia del suelo, por otra. Así: si tenemos $v = 6$ m. por 1", $h = 8$ m., $v_1 = 4.50$, $v_2 = 1.8$ (cascajo corriente) i por consiguiente $v_1 - v_2 = 2.7$, tenemos $v - v_1 = 1.5$, $1.5 : h = \frac{1.5}{8} = 0.50$ metro por metro de altura.

$$\frac{v_1 - v_2}{0.50} = \frac{2.7}{0.5} = 5.4 \text{ metros.}$$

La accion de las aguas i de los remolinos socavarán 5.40 metros mas o ménos.

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Por consiguiente, si hacemos $v_1 = 0.65\,V$, que es el caso mas corriente entre nuestros ríos, tenemos:

$$v_1 = 0.65\,V,\ (v_1 - v_2) = (0.65\,V - v_2) = v_3$$

i por lo tanto

$$(v - v_1) = (v - 0.65\,V), \text{ de donde}$$

$\frac{(v - 0.65\,V)}{h}$ da la proporcionalidad de hondura de socavacion i

$$\frac{(0.65\,V - v_2)}{\frac{(v - 0.65\,V)}{h}} = h_1$$

~~Figure 2. Derivation of both scour formulas~~ in Eqs. 1 and 2 ~~by Santa María (1901~~a~~)~~

Chapter IV distinguishes between riverbeds~~ that admit~~admitting excavations for construction of foundations from those that require water pumping.

Chapter V is devoted to an analysis of scour at bridge foundations under flood conditions, considering observations of the floods occurred in years 1868, 1877, 1878, 1884, 1885, 1888, 1898, 26-29 August 1899, and 1900. A total of 16 study cases ~~are~~ were analysed, including ~~namely those of bridges:~~the Cal y Canto Bridge, built by Spaniard conquerors in 1779 over the Mapocho ~~river~~River near Santiago, Chile, having ~~that~~ collapsed several times (Rosales, 2019).~~, El Salto built in 1854, de las Cucharas over stream Viña del Mar built in 1854, Paso Hondo, Limache with four spans at 15 m, Rabuco, Las Ovejas, El Tablón stream, Lampa, built in 1860 with 121 m in length, San Felipe, Curimón, Troncoso, Tinguiririca built in 1865 and collapsed after the flood of July 13th, 1900 due to the local scour of its central pier, Chimbarongo, Teno Sur, built in 1865 with 3 spans at 30 m, and Río Claro near Yumbel.~~

Chapter VI was devoted to bridges with shallow~~direct~~ foundations. A total of 35 additional study cases were analyzed, ~~namely bridge Los Maquis, built in 1879, Batuco, Chacabuco, Colina where the 1900 flood could not pass because of the sedimentation below the bridge, del Litre, Quebradilla, de Pataguas, de Palos over the Mapocho river, del Ferrocarril del norte, de la Purísima, del Mapocho at San Francisco del Monte, collapsed in 1899, del Maipo with 363 m in length, Angostura, San Francisco, Cachapoal, Antivero, Lircay, and~~including the Maule Bridge over the Maule River near the city of Constitución, Chile, to which Santa María devoted a series of five~~3~~ communications on its construction in years 1898 and 1899~~900~~ (Santa María, 1898 and 1899~~1900~~a,b,c,d), ~~bridges Ñuble, Chillán, Nebuco, Pal Pal, Monteaguila, Laja, Quilacoya, Gomero, Santa María,~~and the ~~-~~Biobío Bridge at Cerro C~~e~~hepe in the city of Concepción, Chile, with 1899 m in length and a sandy streambed (Manby, 1892)~~, Collanco, Paillihue, Biobío at Coihue, Renaico, Huequén, Cautín, and Toltén~~. Figure 2 shows the location of the bridges studied by Santa María. The bridges names are included in Table 1.

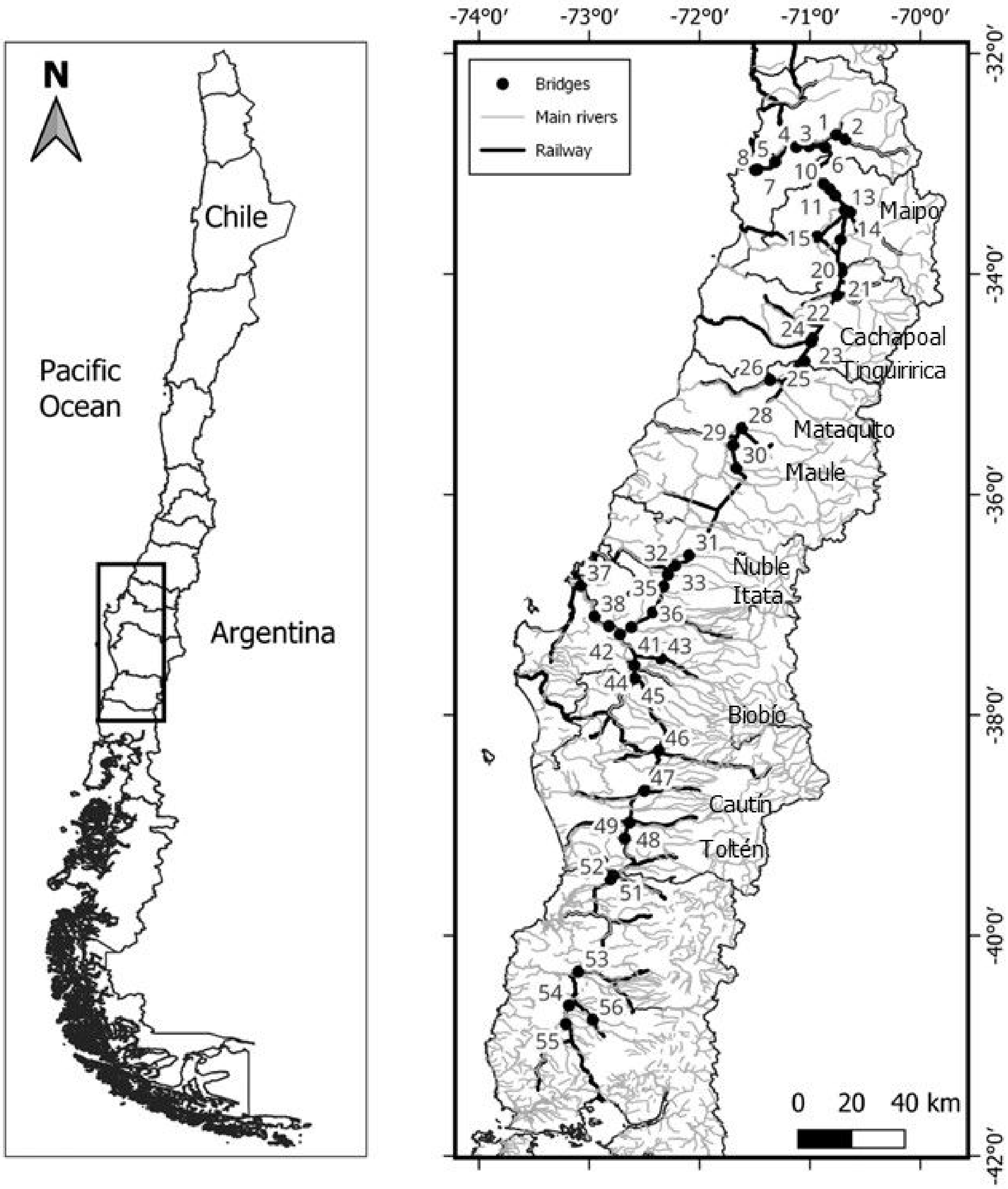


Figure 2. Location of the bridges studied by Santa María

Table 1. Bridges studied by Santa María.

Nr.	Bridge	Nr.	Bridge
1	SAN FELIPE	29	MAULE
2	CURIMÓN	30	BATUCO
3	LAS OVEJAS	31	ÑUBLE
4	RABUCO	32	NEBUCO
5	LIMACHE	33	CHILLÁN
6	LOS MAQUIS	34	COYANCO
7	PASO HONDO	35	PAL PAL
8	LAS CUCHARAS	36	MONTEAGUILA
9	EL TABLÓN	37	BIOBÍO AT CERRO CHEPE
10	CHACABUCO	38	QUILACOYA
11	LAMPA	39	GOMERO
12	COLINA	40	SANTA MARÍA
13	CAL Y CANTO	41	RÍO CLARO NEAR YUMBEL
14	LA PURÍSIMA	42	LAJA
15	MAPOCHO AT SAN FRANCISCO DEL MONTE	43	PAILLIHUE
16	MAIPO	44	BIOBÍO AT COIHUE
17	DE PALOS OVER THE MAPOCHO RIVER	45	RENAICO
18	DEL LITRE	46	EL SALTO
19	QUEBRADILLA, DE PATAGUAS	47	CAUTÍN
20	ANGOSTURA	48	TOLTÉN
21	SAN FRANCISCO	49	DONGUIL
22	CACHAPOAL	50	HUEQUÉN
23	ANTIVERO	51	LEFICAHUE
24	TINGUIRIRICA	52	CIRUELOS
25	CHIMBARONGO	53	RÍO BUENO
26	TENO SUR	54	RAHUE
27	TRONCOSO	55	FORRAHUE
28	LIRCAY	56	CANCURA

Santa María's reasoning for the development of his formulas starts by stating that applications are thought for bridges located along the Central Valley (as to the East the Andes and to the West the Coastal Cordillera would add significant additional difficulties to the development of railroads due to the high slopes), between Santiago city and Toltén River. Santa María points out that during floods the rivers in this area exhibit torrential flows and at the same time, the riverbeds are composed of gravel and boulders. For general scour, he proposes that the flow velocity at the bottom is able to produce general scour if the critical velocity for the inception of sediment motion is exceeded, defining the excess near bed flow velocity $V3$ as the difference between the near bed flow velocity u_*, and the critical near-bed velocity for inception of sediment motion $u_{*,cr}$:

$$V3 = u_* - u_{*,cr} \qquad (1)$$

Accordingly, Santa María observed that if u_* is less than $u_{*,cr}$ the streambed is in equilibrium and no general scour occurs, but if u_* is higher than $u_{*,cr}$, then there can't be equilibrium. The general scour depth, $z_{max,GS}$ was proposed to be proportional to the flow depth, H while the excess velocity needs to be counterbalanced by bottom friction and scour to achieve equilibrium. Santa María proposed:

$$\frac{z_{max,GS}}{H} = \frac{u_* - u_{*,cr}}{z_{max,GS}} \qquad (2)$$

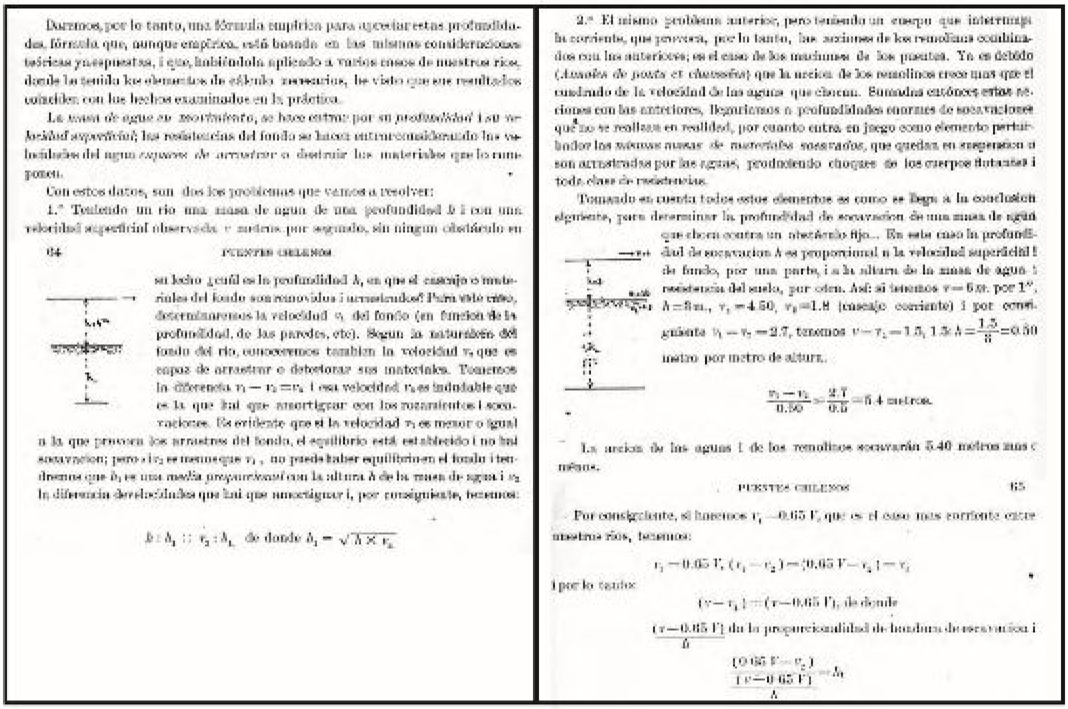
and thus, the general scour depth, $z_{max,GS}$ is:

$$z_{max,GS} = \sqrt{H(u_* - u_{*,cr})} \qquad (3)$$

Further, in case of obstacles placed in the flow, Santa María recognized the formation of eddies that act enhancing scour locally, around the obstacle. He argued that according to the sounding literature, the scouring potential of the eddies increases with the average flow velocity squared, but he doubts such a relation between scour depth and flow velocity, based on unrealistic results he obtained in some applications. Santa María explains that increased internal friction caused by the sediment particles in motion as bed-load and suspended sediment might be responsible for a reduced scour, i.e. not proportional to the flow velocity squared. Next, Santa María proposed that the local scour depth is proportional to the surface flow velocity and to the near-bed flow velocity, as well as to the flow depth and the bed resistance due to friction. Taking the near-bed flow velocity as 0.65 times the surface flow velocity, u_s Santa María proposed the following empirical formula:

$$z_{max,LS} = H\frac{(0.65u_s - u_{*,cr})}{(u_s - 0.65u_s)} \qquad (4)$$

where $z_{max,LS}$ is the maximum local scour depth at a bridge element (pier or abutment). Figure 3 shows the original derivation of both scour equations by Santa María (1901a).



Daremos, por lo tanto, una fórmula empírica para apreciar estas profundidades, fórmula que, aunque empírica, está basada en las mismas consideraciones teóricas ya espuestas, i que, habiéndola aplicado a varios casos de nuestros ríos, donde he tenido los elementos de cálculo necesarios, he visto que sus resultados coinciden con los hechos examinados en la práctica.

La *masa de agua en movimiento*, se hace entrar por su *profundidad* i su *velocidad superficial*; las resistencias del fondo se hacen entrar considerando las velocidades del agua *capaces de arrastrar o destruir* los materiales que lo componen.

Con estos datos, son dos los problemas que vamos a resolver:

1.° Teniendo un río una masa de agua de una profundidad h i con una velocidad superficial observada v metros por segundo, sin ningun obstáculo en

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su lecho ¿cuál es la profundidad h_1 en que el cascajo o materiales del fondo son removidos i arrastrados? Para este caso, determinaremos la velocidad v_1 del fondo (en funcion de la profundidad, de las paredes, etc). Segun la naturaleza del fondo del río, conoceremos tambien la velocidad v_2 que es capaz de arrastrar o deteriorar sus materiales. Tenemos la diferencia $v_1 - v_2 = v_3$ i esa velocidad v_3 es indudable que es la que hai que amortiguar con los rozamientos i socavaciones. Es evidente que si la velocidad v_1 es menor o igual a la que provoca los arrastres del fondo, el equilibrio está establecido i no hai socavacion; pero si v_2 es menor que v_1, no puede haber equilibrio en el fondo i tendremos que h_1 es una media *proporcional* con la altura h de la masa de agua i v_3 la diferencia de velocidades que hai que amortiguar i, por consiguiente, tenemos:

$$h : h_1 :: v_3 : h_1 \quad \text{de donde } h_1 = \sqrt{h \times v_3}$$

2.° El mismo problema anterior, pero teniendo un cuerpo que interrumpa la corriente, que provoca, por lo tanto, las acciones de los remolinos combinados con las anteriores; es el caso de los machones de los puentes. Ya es debido (*Annales de ponts et chaussées*) que la accion de los remolinos crece mas que el cuadrado de la velocidad de las aguas que chocan. Sumadas entónces estas acciones con las anteriores, llegaríamos a profundidades enormes de socavaciones que no se realizan en realidad, por cuanto entra en juego como elemento perturbador las mismas *masas de materiales socavados*, que quedan en suspension o son arrastradas por las aguas, produciendo choques de los cuerpos flotantes i toda clase de resistencias.

Tomando en cuenta todos estos elementos es como se llega a la conclusion siguiente, para determinar la profundidad de socavacion de una masa de agua que choca contra un obstáculo fijo... En este caso la profundidad de socavacion h es proporcional a la velocidad superficial i de fondo, por una parte, i a la altura de la masa de agua i resistencia del suelo, por otra. Así: si tenemos $v = 6$ m. por 1", $h = 8$ m., $v_1 = 4.50$, $v_2 = 1.8$ (cascajo corriente) i por consiguiente $v_1 - v_2 = 2.7$, tenemos $v - v_1 = 1.5$, $1.5 : h = \frac{1.5}{8} = 0.50$ metro por metro de altura.

$$\frac{v_1 - v_2}{0.50} = \frac{2.7}{0.5} = 5.4 \text{ metros.}$$

La accion de las aguas i de los remolinos socavarán 5.40 metros mas o ménos.

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Por consiguiente, si hacemos $v_1 = 0.65\,V$, que es el caso mas corriente entre nuestros ríos, tenemos:

$$v_1 = 0.65\,V, \; (v_1 - v_2) = (0.65\,V - v_2) = v_3$$

i por lo tanto:

$$(v - v_1) = (v - 0.65\,V), \text{ de donde}$$

$\frac{(v - 0.65\,V)}{h}$ da la proporcionalidad de hondura de socavacion i

$$\frac{(0.65\,V - v_2)}{\frac{(v - 0.65\,V)}{h}} = h_1$$

Figure 3. Derivation of scour formulas in Eqs. (2) and (4) by Santa María (1901a)

The proposed scour formulas were validated by comparing, for each study case, the length of foundations with the ~~calculated~~ computed scour, and the occurrence of collapse during floods. Good agreement between the formula's results and the observed behaviour of bridges during floods was obtained.

3.2 The 1908 paper

This study was p~~P~~resented to an audience of over 600 participants at the Fourth Latinamerican and First Pan-American Scientific Congress ~~held in Santiago de Chile between December, 25th 1908 and January, 6th 1909~~ (Holmes, 1909). His ~~, the~~ paper was entitled: "Subterranean waters of torrential rivers. Experiences in Chilean rivers" and was shortly thereafter published in Spanish ~~with the title "Determinación de las profundidades de socavación de las aguas corrientes" (Determination of scour depths by current waters) by Santa María~~ (Santa María, 1909). The paper formally ~~propose~~introduceds~~d~~ the two scour formulas in Eqs. (2) and (4), ~~one~~ for the estimation of ~~the~~ general and local ~~erosion~~ scour at bridges, respectively. ~~in a river, and another one for the estimation of the local scour depth at a bridge pier.~~ Using data corresponding to the recently occurred extreme flood in August, 1900 a validation of the formula for estimation of general ~~erosion~~ scour was presented for bridge sites at bridges Estero de Limache, Estero de Lampa, and Río Claro de Yumbel, and a validation of the formula for the estimation of the maximum scour depth at bridge piers ~~is~~ was presented for bridges Mapocho en Talagante, Nuevo Río Claro de Yumbel, Tinguiririca

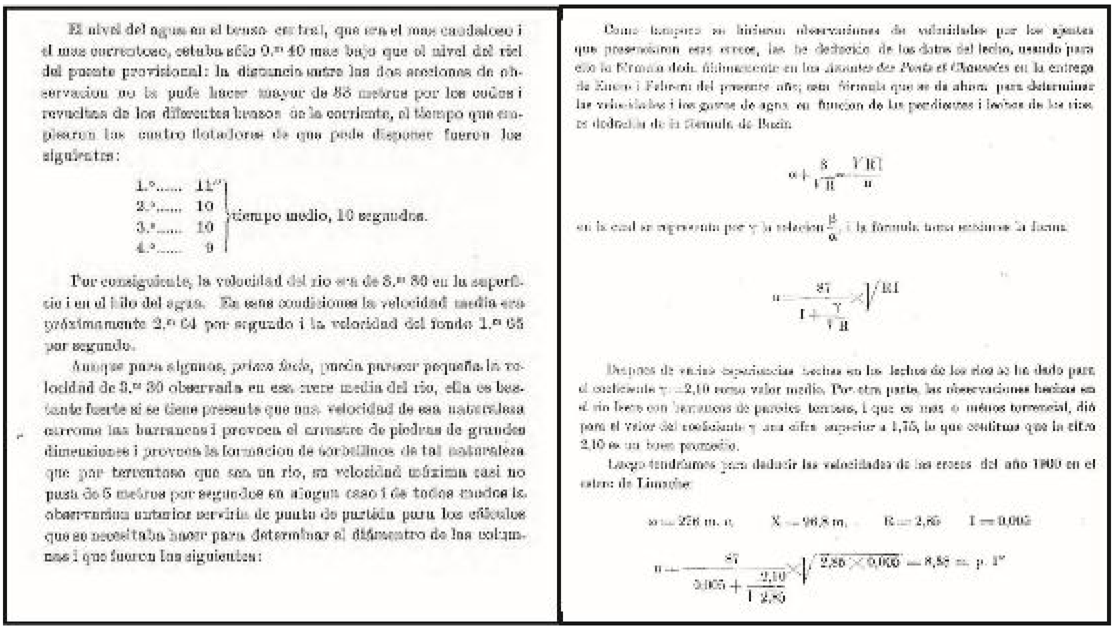
Bridge, and Teno Bridge (please see Table 1 and Figure 2 for location of the bridges).

4 Analysis of Santa María's scour formulas

4.1 Data

Both scour formulas by Santa María are supposed to be applied considering conditions imposed by extreme floods. By the end of the XIX century, ~~in Chile~~ observations of maximum historical events were collected in Chile by public services in a non-systematic way. Usually, watermarks for some sites of interest were available. Besides, a compendium of the climates of Chile by Vicuña (1877) provided (and still does provide) a good description of floods and draughts during the XIX century (Jana et al., 2018).

~~In particular~~The, surface flow velocity was estimated by measuring the time taken by floats ~~ing objects~~ to cover a known distance. In the absence of such measurements, Bazin's formula (Bazin, 1897) was applied. Figure ~~3~~4 shows extracts of Santa María's ~~(1908~~1909) papers, with a description of surface flow velocity measurements (Santa María, 1899b) and the application of Bazin's formula (~~Bazin, 1897~~Santa María, 1909).



El nivel del agua en el brazo central, que era el mas caudaloso i el mas correntoso, estaba sólo 0.m 40 mas bajo que el nivel del riel del puente provisional: la distancia entre las dos secciones de observacion no la pude hacer mayor de 33 metros por los codos i revueltas de los diferentes brazos de la corriente, el tiempo que emplearon los cuatro flotadores de que pude disponer fueron los siguientes:

1.°..... 11"
2.°..... 10
3.°..... 10
4.°..... 9 } tiempo medio, 10 segundos.

Por consiguiente, la velocidad del rio era de 3.m 30 en la superficie i en el hilo del agua. En esas condiciones la velocidad media era próximamente 2.m 64 por segundo i la velocidad del fondo 1.m 65 por segundo.

Aunque para algunos, *prima facie*, podrá parecer pequeña la velocidad de 3.m 30 observada en esa crece media del rio, ella es bastante fuerte si se tiene presente que una velocidad de esa naturaleza socava las barrancas i provoca el arrastre de piedras de grandes dimensiones i provoca la formacion de torbellinos de tal naturaleza que por torrentoso que sea un rio, su velocidad máxima casi no pasa de 5 metros por segundos en ningun caso i de todos modos la observacion anterior serviria de punto de partida para los cálculos que se necesitaba hacer para determinar el diámetro de las columnas i que fueron las siguientes:

Como tampoco se hicieron observaciones de velocidades por los aforos que presenciaron esas creces, las he deducido de los datos del lecho, usando para ello la fórmula dada últimamente en los *Annales des Ponts et Chaussées* en la entrega de Enero i Febrero del presente año; esta fórmula que se da ahora para determinar las velocidades i los gastos de agua en funcion de las pendientes i lechos de los rios, es deducida de la fórmula de Bazin

$$\alpha + \frac{\beta}{\sqrt{R}} = \frac{\sqrt{RI}}{u}$$

en la cual se representa por γ la relacion $\frac{\beta}{\alpha}$, i la fórmula toma entónces la forma

$$u = \frac{87}{1 + \frac{\gamma}{\sqrt{R}}} \times \sqrt{RI}$$

Despues de varias experiencias hechas en los lechos de los rios se ha dado para el coeficiente $\gamma = 2{,}10$ como valor medio. Por otra parte, las observaciones hechas en el rio [illegible] con [illegible] de paredes terrosas, i que es mas o ménos torrencial, dió para el valor del coeficiente γ una cifra superior a 1,75, lo que confirma que la cifra 2,10 es un buen promedio.

Luego tendríamos para deducir las velocidades de las creces del año 1900 en el estero de Limache:

$\omega = 276$ m. c. $\quad X = 96{,}8$ m. $\quad R = 2{,}86 \quad I = 0{,}005$

$$u = \frac{87}{[illegible] + \frac{2{,}10}{\sqrt{2{,}86}}} \times \sqrt{2{,}86 \times 0{,}005} = 3{,}55 \text{ m. p. } 1''$$

Figure 4~~3~~. Extracts of Santa María's ~~(1908)~~ papers, with a description of surface flow velocity measurements (from Santa María, 1899b) and the application of Bazin's formula (Bazin, 1897) (from Santa María, 1909)

Critical velocities for the inception of sediment motion were observed in the field and also obtained from data by Du Buat ~~(Du Buat, 1799)~~ and Telford (Du Buat, 1799), as shown in Figure 5~~4~~.

ANEXO

Velocidades de arrastre dadas por las observaciones de los señores DuBuat i Telford:

	Velocidad de fondo en metro por un 1."
Tierra suelta	0.076
Arcilla parda propia para la cerámica	0.081
Arcilla blanda	0.152
Arenas depositadas por las arcillas de la cerámica	0 162
Arenas del Sena del grosor de un grano de anis	0.108
,, ,, del tamaño de una arveja	0.189
Arena corriente	0 305
Gravas del Sena	0.325
Gravas corrientes finas	0 609
Gravas de 0.025 metro de diámetro máximo	9.650
Gravas gruesas	0.914
Gravas de piedra angulosa de fusil, del tamaño de un huevo de gallina	0.975
Piedra chancada	1.220
Grava aglomerada o esquita blanda	1.520
Rocas en capas o gravas de grandes dimensiones	1.830
Rocas duras	3.950

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Injeniero civil i de minas.

Figure 54. Appendix of Santa María's (1901a) paper with critical near bed flow velocities by Du Buat and Telford

4.2 Structure

Both scour formulas by Santa María~~,~~ introduced the difference between the flow and the critical flow velocity, recognizing an excess velocity as a main scour predictor, ~~similarly to the Du Buat type formulas for sediment transport,~~ thus being much advanced than those scour formulas based on the regime theory, such as those proposed by Lacey (1929), Inglis (1949), and Blench (1962), who represented the flow effect on scour with the specific discharge and flow depth, but much more aligned with modern scour formulas such as those proposed by Jain & Fisher (1980), Melville (1997), and Sheppard et al. (2014), who recognize the importance of an excess velocity parameter for scour. Remarkably, Santa María stated that scour at bridge piers can reach up to 6-8 m under extreme flood conditions observed in Central-South Chile, an upper -limit that corresponds well with the currently accepted envelope for equilibrium scour at 2.5 to 3.0 times the pier diameter.

Santa María recognized the existence of a vertical velocity distribution, and thus knew that the relation between the surface and average flow velocity is not constant, varying between 0.5 and 0.8. He recommended to take a value of 0.65 for flow depths up to 10 m.

General ~~erosion~~ scour was assumed by Santa María to be proportional to the square root of the excess velocity and the flow depth, while local scour at bridge piers was assumed to be proportional to the excess velocity and flow depth. As ~~it~~ is well known today, the pier shape and, especially, its width ~~is an~~are important factors affecting the scour depth. Santa María's scour formula did not include any pier parameter.

4.3 Performance

The local scour formula by Santa María (1901) presented in Eq. (4) was applied to three common flood situations with live bed conditions, deep water relative to pier width, and coarse sediments. Results were compared with those obtained with the scour formulas by Breusers *et al.* (1977), HEC-18 (Arneson *et al.* 2012), Sheppard *et al.* (2014), and Ettmer *et al.* (2015). Table 2 shows the variables for each case.

Table 2. Hydraulic properties defining three application cases

	Case 1	**Case 2**	**Case 3**
***u* (m/s)**	2.5	4	6
***H* (m)**	4	6	10
***D* (m)**	0.8	1.5	1.8
d_s (mm)	10	20	50
u_c (m/s)	1.1	1.9	3.0

where *D* is the pier diameter and d_s is the representative sediment diameter. In the calculations the surface flow velocity in Santa María's equation was assumed equal the average flow velocity. Results are presented in the form of bar charts in Fig. 6.

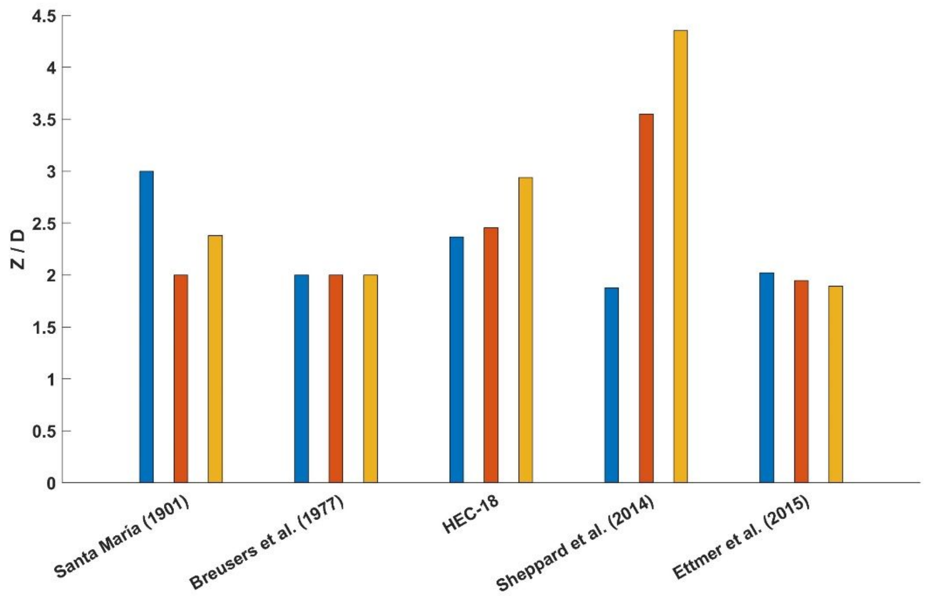

Figure 6. Comparison of normalized local scour depth predictions using the scour formulas by Santa María (1901), Breusers *et al.* (1977), HEC-18 (Arneson *et al.* 2012), Sheppard *et al.* (2014) and Ettmer *et al.* (2015) for particular live-bed scour conditions

Results obtained for the cases defined by the parameters in Table 2, Santa María's scour formula (Eq. 4) compare well with other formulas by Breusers *et al.* (1977), HEC-18 (Arneson *et al.*, 2012), Sheppard *et al.* (2014), and Ettmer *et al.* (2015).

5 Conclusion

Domingo Santa María proposed the first pier scour formulas~~, for general erosion~~ nearly 30 years before Lacey's regime theory, and ~~for bridge scour~~ almost 50 years before Inglis published his scour formula. His equations were developed using field data from several Chilean railway bridges. They ~~, and~~ capture~~d~~ the main effects of the fluid, flow and sediment on scour, ~~in line~~in line with modern formulas currently used worldwide for bridge design. Santa María introduced his scour formulas for the first time to an international audience in 1908, after having verified his findings with observations during the extreme flood ~~occurred in~~of 1900. Thus, Santa María ~~-~~deserves full credit for having develop the first pier scour formulas~~ for general erosion and bridge scour~~.

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Notation

D	=	Pier diameter (m)
d_s	=	Representative sediment particle diameter (m)
H	=	Flow depth (m)
u	=	Flow velocity (ms^{-1})
u_c	=	Critical velocity for the initiation of sediment motion (ms^{-1})
u_*	=	Near bed flow velocity (ms^{-1})
$V3$	=	Excess velocity above the incipient sediment motion condition (ms^{-1})
z	=	Scour depth (m)

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List of tables

Table 1. Bridges studied by Santa María

Nr.	Bridge	Nr.	Bridge
1	SAN FELIPE	29	MAULE
2	CURIMÓN	30	BATUCO
3	LAS OVEJAS	31	ÑUBLE
4	RABUCO	32	NEBUCO
5	LIMACHE	33	CHILLÁN
6	LOS MAQUIS	34	COYANCO
7	PASO HONDO	35	PAL PAL
8	LAS CUCHARAS	36	MONTEAGUILA
9	EL TABLÓN	37	BIOBÍO AT CERRO CHEPE
10	CHACABUCO	38	QUILACOYA
11	LAMPA	39	GOMERO
12	COLINA	40	SANTA MARÍA
13	CAL Y CANTO	41	RÍO CLARO NEAR YUMBEL
14	LA PURÍSIMA	42	LAJA
15	MAPOCHO AT SAN FRANCISCO DEL MONTE	43	PAILLIHUE
16	MAIPO	44	BIOBÍO AT COIHUE
17	DE PALOS OVER THE MAPOCHO RIVER	45	RENAICO
18	DEL LITRE	46	EL SALTO
19	QUEBRADILLA, DE PATAGUAS	47	CAUTÍN
20	ANGOSTURA	48	TOLTÉN
21	SAN FRANCISCO	49	DONGUIL
22	CACHAPOAL	50	HUEQUÉN
23	ANTIVERO	51	LEFICAHUE
24	TINGUIRIRICA	52	CIRUELOS
25	CHIMBARONGO	53	RÍO BUENO
26	TENO SUR	54	RAHUE
27	TRONCOSO	55	FORRAHUE
28	LIRCAY	56	CANCURA

Table 2. Hydraulic properties defining three application cases

	Case 1	Case 2	Case 3
U (m/s)	2.5	4	6
H (m)	4	6	10
D (m)	0.8	1.5	1.8
d_s (mm)	10	20	50
U_c (m/s)	1.1	1.9	3.0

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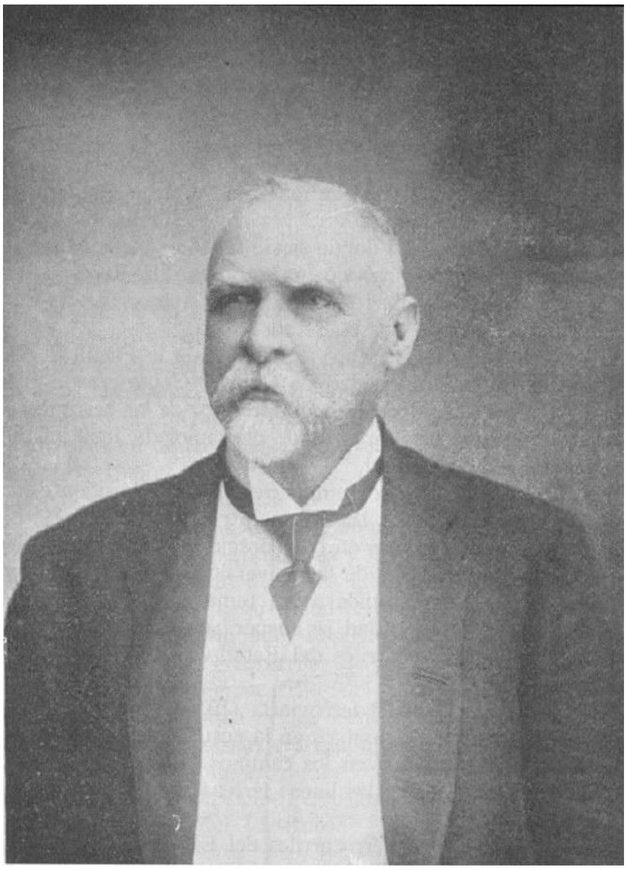


Figure 1. Domingo Víctor Santa María (1854-1919) (Source: Instituto de Ingenieros de Chile, 1919)

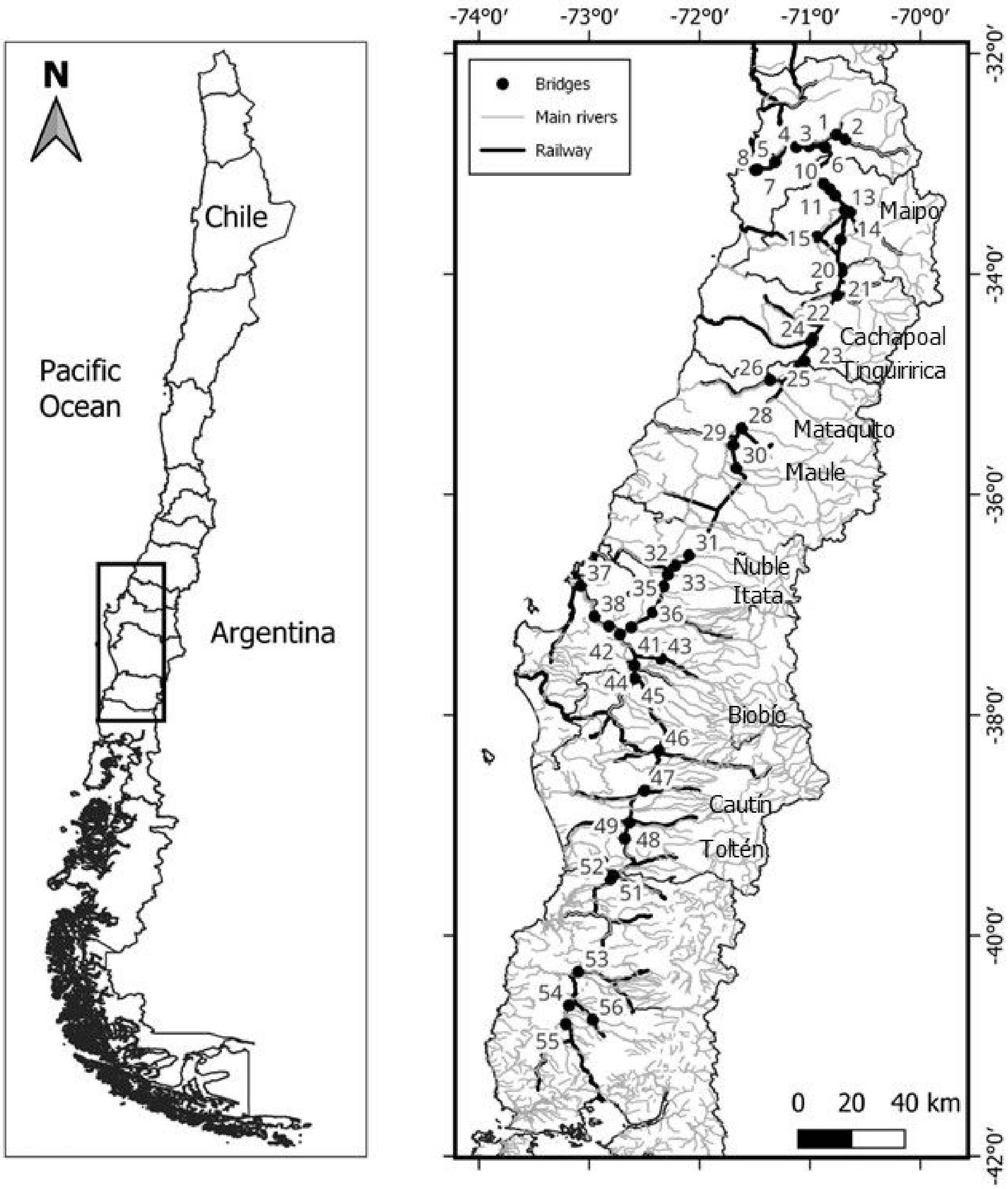


Figure 2. Location of the bridges studied by Santa María

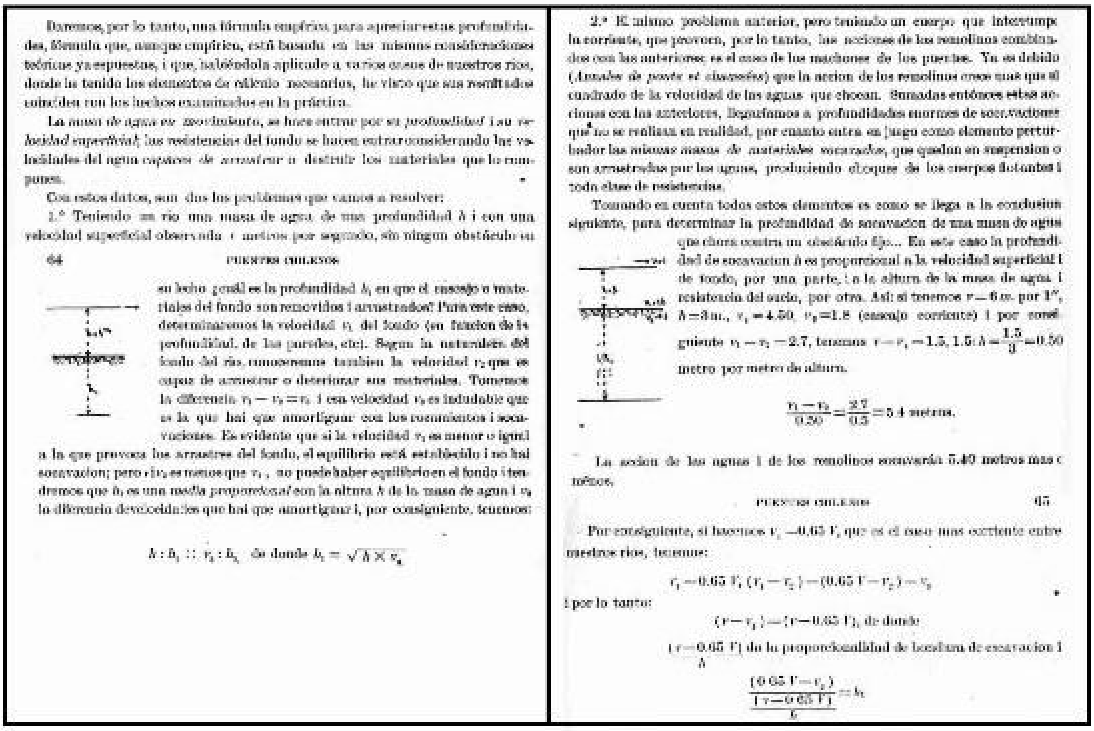
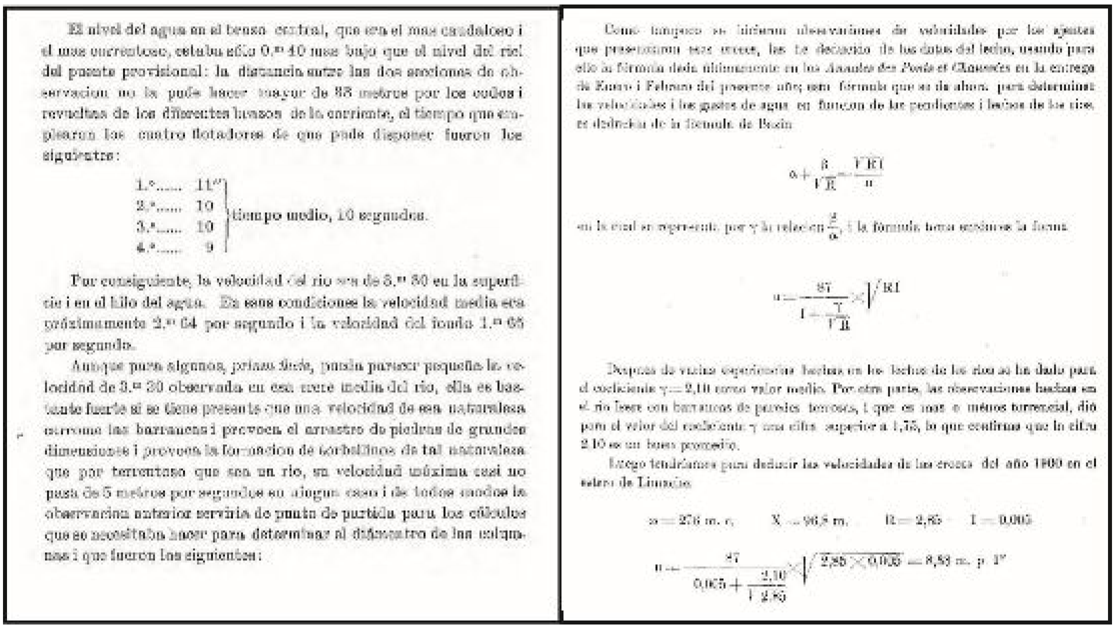


Figure 3~~2~~. Derivation of scour formulas in Eqs. 1 and 2 by Santa María (1901a)~~Derivation of both scour formulas by Santa María (1901)~~



El nivel del agua en el brazo central, que era el mas caudaloso i el mas correntoso, estaba allí 0.m 40 mas bajo que el nivel del riel del puente provisional: la distancia entre las dos secciones de observacion no la pude hacer mayor de 88 metros por los codos i revueltas de los diferentes brazos de la corriente, el tiempo que emplearon los cuatro flotadores de que pude disponer fueron los siguientes:

1.°..... 11″
2.°..... 10
3.°..... 10
4.°..... 9
} tiempo medio, 10 segundos.

Por consiguiente, la velocidad del rio era de 8.m 80 en la superficie i en el hilo del agua. En esas condiciones la velocidad media era próximamente 2.m 64 por segundo i la velocidad del fondo 1.m 65 por segundo.

Aunque para algunos, prima facie, pueda parecer pequeña la velocidad de 3.m 30 observada en esa parte media del rio, ella es bastante fuerte si se tiene presente que una velocidad de esa naturaleza corroe las barrancas i provoca el arrastre de piedras de grandes dimensiones i provoca la formacion de torbellinos de tal naturaleza que por torrentoso que sea un rio, su velocidad máxima casi no pasa de 5 metros por segundo en ningun caso i de todos modos la observacion anterior serviria de punto de partida para los cálculos que se necesitaba hacer para determinar el diámetro de las columnas i que fueron los siguientes:

Como tampoco se hicieron observaciones de velocidades por los ajustes que presentaron esas crecES, las he deducido de los datos del lecho, usando para ello la fórmula dada últimamente en los *Annales des Ponts et Chaussées* en la entrega de Enero i Febrero del presente año; esta fórmula que se da ahora para determinar las velocidades i los gastos de agua en funcion de las pendientes i lechos de los ríos, es deducida de la fórmula de Bazin

$$\alpha + \frac{\beta}{\sqrt{R}} = \frac{\sqrt{RI}}{u}$$

en la cual se representa por γ la relacion $\frac{\beta}{\alpha}$, i la fórmula toma entónces la forma

$$u = \frac{87}{1 + \frac{\gamma}{\sqrt{R}}} \times \sqrt{RI}$$

Despues de varias experiencias hechas en los lechos de los rios se ha dado para el coeficiente $\gamma = 2{,}10$ como valor medio. Por otra parte, las observaciones hechas en el rio [illegible] con barrancos de paredes terrosas, i que es mas o ménos torrencial, dió para el valor del coeficiente γ una cifra superior a 1,75, lo que confirma que la cifra 2,10 es un buen promedio.

Luego tendríamos para deducir las velocidades de las crecES del año 1900 en el estero de Limache

$\omega = 276$ m. c. $\quad X = 96{,}5$ m. $\quad R = 2{,}85 \quad I = 0{,}005$

$$u = \frac{87}{0{,}065 + \frac{2{,}10}{\sqrt{2{,}85}}} \times \sqrt{2{,}85 \times 0{,}005} = 8{,}53 \text{ m. p. } 1''$$

Figure 4~~3~~. Extracts of Santa María’s (1908) papers, with a description of surface flow velocity measurements (from Santa María, 1899b) and the application of Bazin’s formula (Bazin, 1897) (from Santa María, 1909) ~~Extracts of Santa María (1908) paper, with a description of surface flow velocity measurements and the application of Bazin’s formula~~

ANEXO

Velocidades de arrastre dadas por las observaciones de los señores DuBuat i Telford:

	Velocidad de fondo en metro por un 1.ª
Tierra suelta	0.076
Arcilla parda propia para la cerámica	0.081
Arcilla blanda	0.152
Arenas depositadas por las arcillas de la cerámica	0 162
Arenas del Sena del grosor de un grano de anis	0.108
,, ,, del tamaño de una arveja	0.189
Arena corriente	0 305
Gravas del Sena	0.325
Gravas corrientes finas	0 609
Gravas de 0.025 metro de diámetro máximo	9.650
Gravas gruesas	0.914
Gravas de piedra angulosa de fusil, del tamaño de un huevo de gallina	0.975
Piedra chancada	1.220
Grava aglomerada o esquita blanda	1.520
Rocas en capas o gravas de grandes dimensiones	1.830
Rocas duras	3.950

DOMINGO V. SANTA MARÍA
Injeniero civil i de minas.

Figure 54. Appendix of Santa María's (1901a) paper with observed critical near bed flow velocities by Du Buat (1799) and Telford

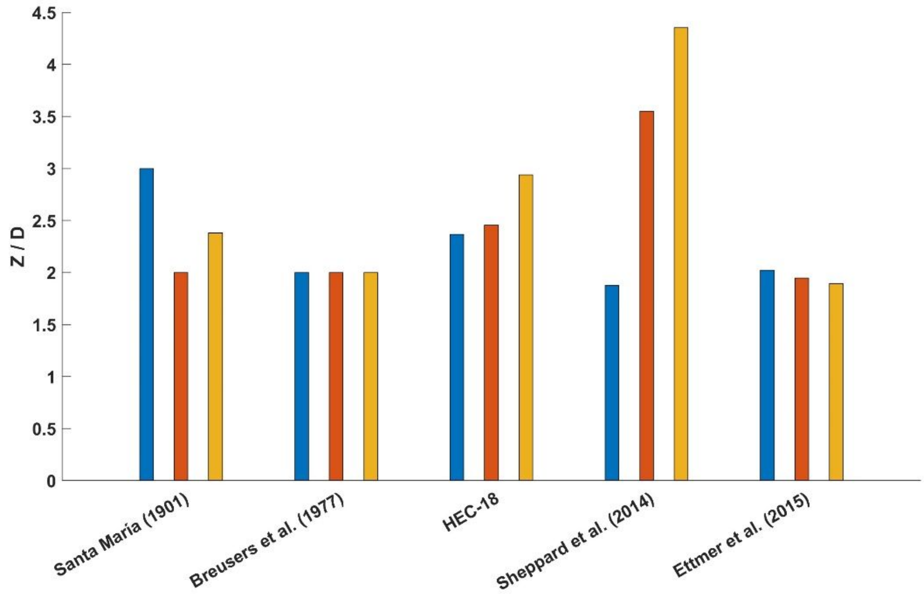


Figure 6. Comparison of normalized local scour depth predictions using the scour formulas by Santa María (1901), Breusers *et al.* (1977), HEC-18 (Arneson *et al.* 2012), Sheppard *et al.* (2014) and Ettmer *et al.* (2015) for particular live-bed scour conditions