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Relevance of the use of measurement units and orders of magnitude in the training of civil engineers

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Abstract. Worldwide, a typical civil engineering program focuses in formal, natural, and applied sciences within an environment of ethical and social responsibility. Mathematics and computer sciences are the main formal sciences. The most widely used natural sciences are physics, earth science, and chemistry. On the other hand, a student who begins the professional cycle of the program must develop skills in applied science to solve practical problems. Complex processes and concepts requiring skills related to mathematics and physics must be developed. Such processes and concepts demand an impeccable handling of operations which involve diverse precision degrees, measurement units and a high variety of basic and derived quantities. This work describes the identification and classification of the main errors made by students when solving written exams applied in a natural environment of structural design courses. Data were collected during four years at a university in Colombia. Report of errors was grouped into five categories named modelling, quantities, regulation, signs, and others. Collected errors were evaluated qualitatively and quantitatively. In addition, each error was assigned to a risk level (high, intermediate, low) according to its potentiality to generate catastrophic errors in professional practice. The quality and number of observed errors seem to be correlated with the time of year in which they occur. On the other hand, the high-risk errors resulted to outweigh the two lower risk levels. This finding is worrying and serves as the basis for making an urgent call to review the way of teaching and its relationship with practical results. In synthesis, this study presents a novel manner to study the formation errors in engineering civil programs. In the near future, it is expected to use the results of this research to propose a procedure for the design and feedback of teaching strategies consistent with the evaluation objectives of each course.

1. Introduction

There is worldwide consensus on what should be taught in a civil engineering program. A typical program should offer training in formal, natural, and applied sciences embedded within a transversality of ethical and social responsibility. Among the formal sciences, mathematics and computer sciences stand out, while the most used natural sciences are physics, earth sciences, and chemistry [1,2]. On the other hand, applied sciences, which apply formal and natural sciences to solve practical problems, constitute an important differentiating nucleus of civil engineering with respect to other engineering. At present, the applied sciences of civil engineering can be grouped according to their focus in seven areas: structures, construction, geotechnics, hydraulics, sanitary, environmental and transportation [3-5]. In the formation of each branch, the skill and aptitude for the calculations required for solving problems varies in complexity and scope. The structures branch is the one that demands more depth of concepts and processes requiring mathematics and physics. However, all areas require impeccable handling of



operations that involve varying degrees of precision and relate a high variety of basic and derived quantities to their respective units [1,6].

Solution of civil engineering problems requires a high degree of responsibility and adequate professional skills from the person who solves them. The cost of involved resources, assets, and spaces affected during the feasibility studies, design, construction, maintenance, and final disposal of works, is usually high in monetary, environmental, and social terms [7,8]. The failure of an asset produced by civil engineering can significantly affect the balance of a region or even an entire country. For example, in Colombia, where the proper functioning of road network is vital, the failure of a bridge can cause losses of human lives, supplies, exports, emergency care, and cause a myriad of problems with a domino effect. For this reason, all civil engineering works processes are usually reviewed and controlled in multiple stages to identify and correct errors that could be catastrophic.

In training of civil engineers, the understanding of the meaning and application of measurement quantities, proper handling of units and correct judgment of domains and ranges represented in orders of magnitude, constitute fundamental aspects [9-11]. A weak formation in these scopes can generate what might be called a weak link in the problem-solving chain [12-14]. This work presents the errors identified and classified by the authors during four years of teaching in courses in the structures branch of a civil engineering program. Also, a discussion related to those observations is presented attempting to visualize and propose ideas for including these aspects within the evaluation objectives of each course.

2. Quantities, measurement units and orders of magnitude for civil engineers

Physical quantities are of high importance in civil engineering applications. Their expressions in the form of scalars, vectors or tensors necessarily require the definition of measurement units, required compatibility and valid orders of magnitude according to the observed reality. To delimit these expressions, in civil engineering the basic quantities of length, mass, time and temperature are used. For the same effect, the derived quantities are area, volume, velocity, acceleration, flow, force, pressure, angles, frequency, and dimensionless proportions [9,11,12].

Although most applied concepts of civil engineering are constructed using derived quantities, each training area has its own measurement and scaling peculiarities. In this sense, it is necessary to resort to some accepted worldwide system of units that standardizes its interpretation and use. According to this, the most widespread canon for the measurement units of civil engineering quantities, the international system of units (SI), is used in this work [12].

Coherence of units and scale assignment (prefixes) are of high importance since they facilitate the calculations and the association and memorization of quantities in practice. The scale assignment of the units is done considering the observed historical values of each quantity and, although multiples are usually chosen to reduce the number to an equivalent quantity, there are some subjects in which the use of submultiples is more appropriate. For example, when studying the bending moment resistance of a beam section, the multiple of thousands is usually used in its units, expressing its value in KN·m. In contrast, in practice the flow rate of a small faucet is usually expressed in l / min which combines a SI prefix applied to the metric system with a non-SI multiple applied to a SI unit of time.

3. Methodology

This work is based on a case study carried out over 4 years in structural design's courses at the Universidad Francisco de Paula Santander, San José de Cúcuta, Colombia. In that period, one of the two existing structural design courses of the civil engineering program was permanently observed. The record of errors was made by evaluating the written solution of three midterms exams during each semester in an activity that combined observation and expert judgment. Once the errors were recorded, they were classified and processed calculating their and their relative frequency of appearance. As part of the global research, a random code was assigned to each student to avoid identification bias. Then, the trend of results of each semester group and the composite group was considered, without including discrimination for recidivism.

Report of errors was grouped into five categories, each one labeled with a simple name. Name and coverage of each category is summarized as follows [7,12,14]:

- Modelling: modelling errors related to the restriction of degrees of freedom, assignment of geometric dimensions, construction and interpretation of diagrams and graphic expression.
- Quantities: errors in handling quantities according to coherence, scaling, order of magnitude, and domain and range of loads, internal forces (bending moment and shear force) and reinforcement quantities.
- Regulation: errors of interpretation and application of conditions of the NSR-10 regulation [7], mainly concerning to reinforcement configuration and logical relationships between resistance and demand.
- Signs: mathematical sign errors and ignorance of their effect in practice, mainly related to catastrophic failures due to reversal of signs when configuring the reinforcement.
- Others: incomplete solution of the exam, change of solution context, and absence of some solution processes.

A qualitative and quantitative description was applied to each category. The qualitative classification considered two manifestations of error: Fundamental error and form error. Fundamental errors can be catastrophic in the sense that they are promoters of structural failure. Form errors do not usually have a significant effect on practical results. Figure 1 shows an example of each type of error. In the upper part of the figure, there is a poorly detailed reinforcement due to insufficient resistance in the upper right part that will cause the element to fail. On the other hand, although the bending moment diagram of the lower part has an error in its shape, the reinforcement detailing shown in the left lower part of figure guarantees adequate resistance of the element. The quantitative classification was made with the help of descriptive statistics.

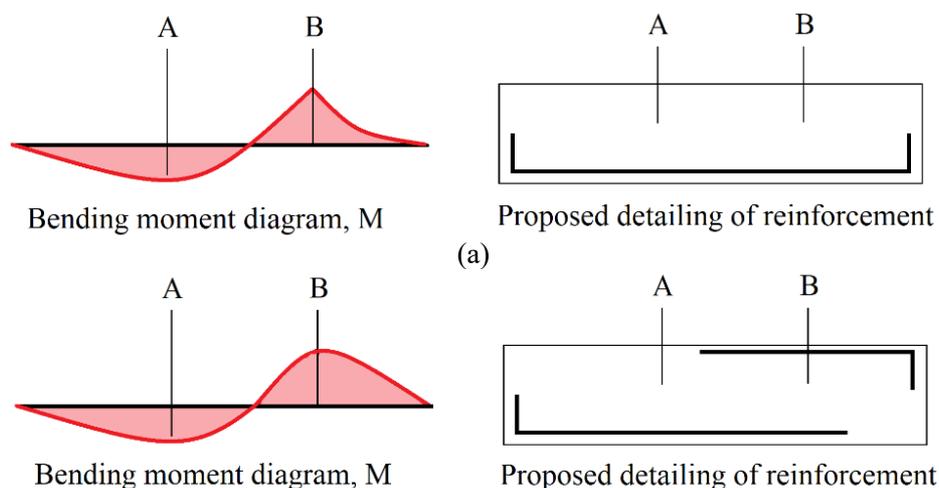


Figure 1. Example of qualitative errors classification; (a) fundamental error, (b) form error.

4. Results

The study population was defined by 1695 partial exams of existing groups of the same course. The sample size was set at 545 applied exams, which corresponds to 32% of the population. 1873 errors made by 90% of the total students who took the tests were identified. Each student who made some type of error had an average of 2.2 errors per exam with a coefficient of variation (CV) of 66%.

Table 1 presents two basic statistical measures of the errors observed according to the category and the time of year. To express the results in an easy-to-read form, they were normalized by dividing the

number of errors of each category by the total number of errors in each school period (semester). The statistical measures for the four years were calculated using the normalized averages for each semester.

The parameters shown in Table 1 are defined as: S is the arithmetic mean of error of each category with respect to the total of errors of all categories without discriminating time of year; CV is the coefficient of variation of data of the same category without discriminating time of year; r: correlation coefficient between data from the same category without discriminating time of year; S#1 is the arithmetic mean of error of each category with respect to the total of errors of all the categories for the first semester of the year; CV1 is the coefficient of variation of data of the same category for the first semester of the year; S#2 is the arithmetic mean of error of each category with respect to the total of errors of all the categories for the second semester of the year; CV2 is the coefficient of variation of data of the same category for the second semester of the year.

The errors variation trend made by the students during the observation period of this research was also studied and its results are shown in Figure 2.

Table 1. Statistics of observed errors according to each category.

Type of error	S	CV	r	S#1	CV1	S#2	CV2
Modelling	21%	18%	0.90	23%	13%	18%	16%
Quantities	49%	7%	1.00	51%	6%	46%	24%
Standards	12%	26%	-0.41	11%	4%	13%	119%
Signs	8%	52%	-0.72	6%	71%	10%	5%
Others	10%	25%	-0.91	8%	21%	12%	9%

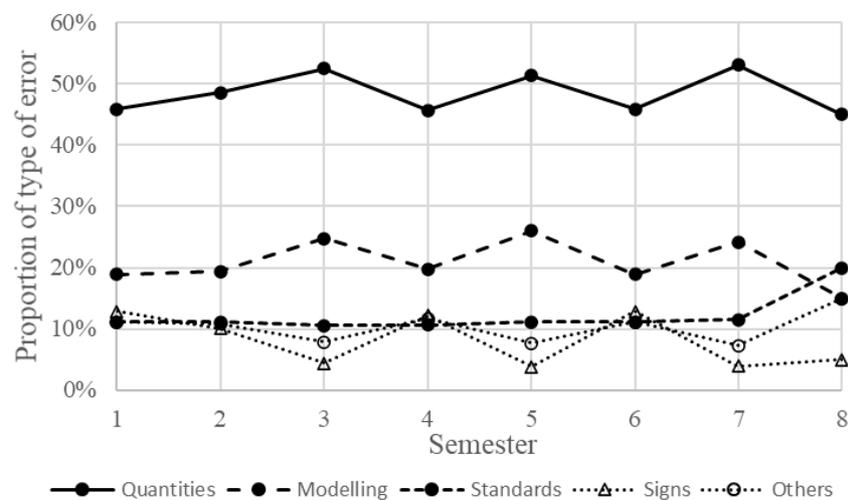


Figure 2. Variation of errors of each category in the observation window.

As can be seen from the results, the larger number of errors belong to the category "quantities" which describes errors related to the use of measurement units and orders of magnitude of quantities. For this reason, this work focused on identifying the possible effects of these errors upon the training and practice of civil engineers. To do this, errors were classified according to their manifestation (fundamental or form) and a degree of risk was assigned according to the potential harmful effects for the professional practice. The risk classification was made according to the following definitions:

- Low risk: the error is usually linked to form and is unlikely to produce catastrophic errors in professional practice. It is assigned a grade equal to 1.
- Intermediate risk: the error combines fundamental and form manifestation and can cause catastrophic errors in professional practice. It is assigned a grade equal to 2.

- High risk: the error is fundamental and causes catastrophic errors in professional practice. It is assigned a grade equal to 3.

Figure 3 presents the variation in risk associated with the errors found during the duration of the investigation. The average and coefficient of variation of the risk-promoting errors were found to be 42% (CV = 29%), 15% (CV = 19%) and 43% (CV = 33%) for risk 1, 2 and 3 respectively. The main problems of the category of quantities were related to magnitude, multiples and submultiples, number of decimals and axiom of order.

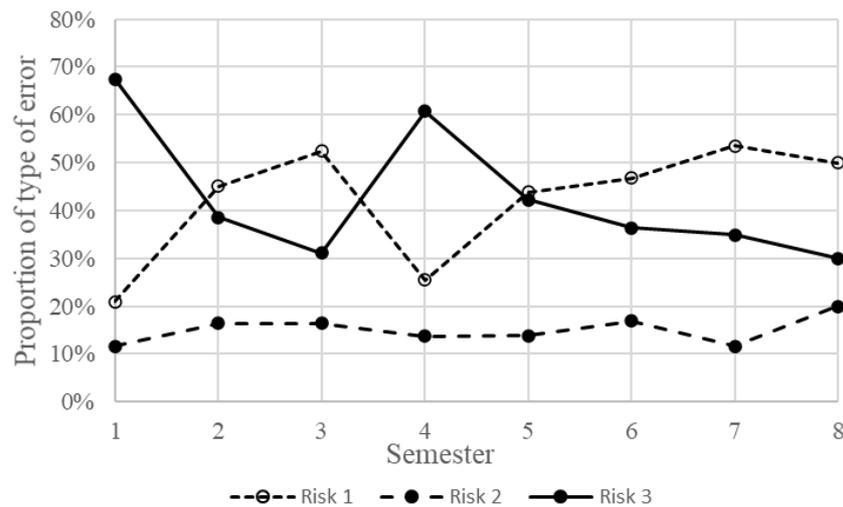


Figure 3. Variation in risk related to errors through time.

5. Discussion

It is important to understand the nature and scope of form errors form to infer their effect on the practical applications of civil engineering. There are form errors that seem to show deep psychological conflicts which manifest as apathy or rejection to learn only as a requirement. It is necessary to continue studying the problem of form errors to elucidate such error promoters that are typical of the hidden curriculum. The most common observed errors associated with the category “quantities” were:

- Disproportionate order of magnitude, in some cases, up to double or half than the correct value.
- Excessive number of decimal places for large quantities.
- Confusion when applying the order axiom to information read from diagrams.

The underlying information of the exposed errors must be contrasted with other error categories defined in this study. Thus, for example, a magnitude error of a reaction force could come from an error in the assignment of type of supports during modeling and, this in turn, come from a incorrect interpretation of standards which impose practical conditions on the problem. When this is considered, the error quality can change dramatically.

From Table 1, it can be inferred that there is a strong and positive correlation between the quantity and modeling categories, which seems to confirm what is described in the previous paragraph. In contrast, it is observed that the sign errors have a negative correlation with the quantity errors. This seems to indicate that as more quantity errors are observed, the expected sign errors will tend to be few.

The quality and number of observed errors seem to be correlated with the time of year in which they occur. For example, modelling and quantity errors are highest at the first part of the year, while sign errors tend to be fewer. This could be related to the preponderance of promotion of high school students in the last months of the year or to culture. These hypotheses constitute the basis of future research works that will help understand the subject.

Figure 3 seems to show a variable, almost cyclical trend of errors associated with a certain level of risk. Perhaps, this trend is closely related to the one discussed in the previous paragraph. It is important to note that the high-risk errors (level 3) outweigh the two lower risk levels. This finding is worrying and serves as the basis for making an urgent call to review the way of teaching and its relationship with practical results.

6. Conclusions

Identification, classification, and analysis of errors related to learning processes of civil engineering students were done. Errors were classified into five categories: modelling, quantities, standards, signs, and others. The category "quantities" turned out to be the one that showed the most errors. In this category, errors were included in the handling of quantities according to coherence, scaling and order of magnitude of units and domain and range of loads, internal forces, and reinforcement quantities.

The most common errors associated with quantities were a) Disproportionate order of magnitude in some cases up to double or half than the correct value, b) Excessive number of decimal places for large quantities, c) Confusion when applying the axiom of order when reading information from diagrams. The relationship between different types of errors should be furtherly investigated. For example, a quantity error can be closely related to a modelling error and, this in turn, come from some practical restriction that can only be overcome with the memorization of regulations.

A strong and positive correlation was observed between quantity errors and modeling errors. On the other hand, sign errors show a negative correlation with quantity errors. This seems to indicate that, the larger the quantity errors are observed, the lower the sign errors. The time of year in which the tests are performed seems to have an impact on the results. For example, modelling and quantity errors are highest at the beginning of the year, while sign errors show to be fewer. It is probable that high school students' promotion made during the last months of the year or culture have an influence on what is observed. Errors associated to a certain level of risk show an almost cyclical trend over time. In this sense, it is worrying to note that high-risk promoter errors (level 3) exceed the two lower risk levels.

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