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Conversion from Ultimate Limit State to Serviceability Limit State for Foundation Design: Critique of Current Practice and Codes/Standards

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ABSTRACT

The adoption and utilisation of ultimate loads for serviceability limit state conditions in foundation design has become a practice due to the cumbersome and time consuming processes and procedures for load computation and estimation. This practice has resulted in safe but uneconomic foundation designs since large values of loads imply increased base areas of footings or number of piles for such building foundation stability. However, for safe and economic designs of foundations, the need for the conversion of ultimate limit loads to serviceability limit state conditions is important. To address that, this paper reviews the extant literature and body of knowledge to understand the extent of practice and documentation. It is revealed that some available conversion factors have been identified and detailed. Also, previous and recent developments on this fundamental design parameter have been summarised and highlighted, including the extent of application of this parameter. These show gross shortcomings in the conversion of ultimate limit state loads to serviceability limit state loads. Therefore, until appropriate conversion factors that are applicable and acceptable are evolved, to aid speedy conversion of loads aggregated at the ultimate limit state to service loads, the implication is continuous uneconomic foundation designs at the expense of building clients.

Keywords: foundation design, conversion factors, ultimate loads, serviceability loads, codes of practice

INTRODUCTION

The adoption and utilisation of ultimate loads for serviceability limit state conditions in foundation design has become a trend. This is as a result of the cumbersome and time consuming processes and procedures of load computation and estimation (Oyenuga, 2001). The structural engineer thus having a lot of design jobs at hand and being under pressure to complete and deliver such design jobs within very limited period of time yet poised to deliver designs that meet required and acceptable standard for structural safety, stability and economy.

It is very obvious that this trend has, to a larger extent, resulted in uneconomic designs. A slight increase in design load could lead to increase in base area of footing or number of piles required for foundation stability. The decision to change a foundation type, such as from strip to pad, pad to raft or raft to pile is largely influenced by the magnitude of loads transmitted to the foundations (Puolos, 2016). When such loads are ultimate (factored) loads, more reinforcement and larger base areas and thicknesses will be required but less if such loads are service loads. Most codes such as BS 8004 (1986), ACI 318-11 (2011), Eurocode 1997 Part 1 (2004) among others require that the base area of footings or the number and arrangement of piles be determined from un-factored forces and moments transmitted by footing to soil.

Also, most clients are cost conscious; therefore, uneconomic structural designs that pertain to substructure works could affect their disposition towards acceptance and adoption of structural designs for construction purposes. By this, the structural designer is compelled to give adequate consideration to economy in design.

According to Oyenuga (2001), loads from the superstructure are often aggregated at the ultimate limit state and the conversion to serviceability limit state becomes relatively difficult or very cumbersome. To obtain service loads at foundation level, either the actual (un-factored) foundation loads are computed or the ultimate loads are un-factored using a conversion factor, the later being a better option considering its time saving and less cumbersome processes and procedures.

The introduction of conversion factors provide the basis for converting ultimate loads to service loads, thus saving the structural designer time and stress encountered when computing service loads. However, these conversion factors could have limitations which could successfully place restrictions on the extent to which they could be utilised, thus necessitating the need to review the factor(s), evaluate them and make case for suitable and appropriate conversion factors where necessary. Values of conversion factors are a function of the magnitude of different types of loads and as such, a singular value may not be relied upon. It is thus also important that appropriate conversion factor values be sought for or evolved where possible so as to provide the much needed data for load conversion purposes.

LITERATURE REVIEW

Load Conversion Factors

From experience, Oyenuga (2001) has found that the ultimate load could be divided by a factor of 1.46 to convert to serviceability limit state, which is within reasonable practical limits. Furthermore, the value may increase to 1.49 as the structure live load increases to 5.0kN/m^2. However, he cautions engineers to be careful in the application of this factor and suggests that a computer program be developed to generate values of the conversion factor for various values of live loads.

BS 5950 (2000) in clause A6 states that the ratio, factored load/serviceability load is generally about 1.50 with a minimum of 1.40, implying that 1.40 ≤ ratio ≤ 1.50. However, the conditions and rules governing its application are not specified. Also, the code deals with steel design and not reinforced concrete. Nevertheless, value of conversion factor by Oyenuga (2001) fall within the range specified here.

Quimby (2008) proposes a factor referred to as Composite Load Factor, CLF, which is the ratio of load combination result (P_u or P_a) to the algebraic sum of the individual load components ($P_{s,equiv}$ or $P_{s,\ eq}$). According to him, ultimate loads cannot be directly compared with service loads. Either the service loads must be factored or the ultimate loads be un-factored if they are to be compared. The computations of CLF given are as shown in Table 1 below.

Table 1: Computation of Composite Load Factor

LRFD	ASD
$P_u = P_{s,equiv}$ * CLF_{LRFD}	$P_a = P_{s,equiv}$ * CLF_{ASD}
$CLF_{LRFD} = P_u/P_{s,equiv}$	$CLF_{ASD} = P_u/P_{s,equiv}$

Source: Quimby (2008)

Where LRFD is load and resistance factor design, ASD is allowable stress design, $P_{s,equiv}$ = algebraic sum of all the service load components (i.e. $P_{s,equiv}$ = D + L +....), and CLF = Composite Load Factor for each case. He further added that the Composite Load Factor, CLF $= P_u / P_{s,equiv}$ varies with the relative magnitudes of the different types of loads. However no specific value was specified for the conversion factor.

The International Code Council – Evaluation Service, ICC-ES (2012) revised the Acceptance Criteria for Mechanical Anchors in Concrete Elements (AC193). The revised AC 193 detailed conversion factor employed in an equation (clause 6.4.3.1) used to establish allowable loads. The equation is $T_{allowable,ASD} = (\phi N_n)/\alpha$

Where $T_{allowable,ASD}$ = Allowable tension load (lbf or kN)

N_n = lowest design strength of an anchor or anchor group in tension as determined in accordance with ACI 318 Appendix D and 2012 IBC Section 1905.1.9, 2009 IBC Section1908.1.9 or 2006 IBC Section 1908.1.16.

α = Conversion factor calculated as a weighted average of the load factors for the controlling load combination. In addition, α shall include all applicable factors to account for non-ductile failure modes and required over-strength.

Here, the conversion factor is not a product of experience but a weighted average of load factors for any given controlling load combination. No value for conversion factor was specified but when individual load components are known and a load combination is defined, the conversion factor can easily be computed. However, where the load components are aggregated at ultimate limit state, the service loads will have to be computed first before the conversion factor can be obtained.

The concept of conversion factor presented here allows for variation in the controlling load combination equation and load components, hence it can be said to be globally applicable and acceptable.

From the review above, the following can be deduced:

i. Ultimate loads can only be compared to service loads when they are un-factored.
ii. The conversion factor is a ratio of the ultimate (factored) load to the service (un-factored) load.
iii. The conversion factor is also a weighted average of the load factors for any given controlling loads combination.
iv. Service loads can be obtained by dividing ultimate loads by a conversion factor.
v. The conversion factor varies with the relative magnitude of the different type of loads.

Major Codes of Practice and Standards

This review is carried out to seek existing and workable conversion factor(s) and to determine their extent and scope of application. Since codes and standards specify guidelines and minimum performance requirements for design and construction, a review of some major steel and concrete design codes is necessary and imperative.

BS 8110 Part 1:1997 (Structural Use of Concrete Part 1: Code of Practice for Design and Construction) provides recommendation for structural use of concrete in buildings and structures, excluding bridges and structural concrete made with high alumina cement. In this code, only partial safety factors are specified alongside their values for dead, live and imposed loads respectively. However, conversion factors are not provided nor specified.

BS 8004:1986 (Code of Practice for Foundations) provides recommendations for the design and construction of foundations for the normal range of buildings and engineering structures. This code in Clause 2.3.2.4.1 recommends un-factored values of loads to be used for foundation design and not the factored loads. However, simplified methods of computing service loads have not been discussed. Also, conversion factors have not been specified or recommended.

EN1990: 2002 (Eurocode – Basis of Structural Design) has establishes principles and requirements for serviceability and durability for structures, describes the basis for their design and verification and has Conversion factor has been considered in Clause 6.3.3 as a parameter required for computing the design value of a material or product property and is denoted by η, representing the mean value of conversion factor taking into account volume and scale effects, effects of moisture and temperature and any other relevant parameter. However, the conversion factor contained in this code does not apply to loads but material or product property.

EN1991-1-1 (2002) (Actions on Structures - Part 1:General Actions – Densities, self weight and imposed loads for buildings) provides guidance on actions for the design of buildings and civil engineering works, including some geotechnical aspects of density of construction materials and stored materials, self weight of construction works, and imposed loads for buildings. However, load factors and load combinations have not been detailed in this code. Also, load conversion factors have not been discussed or recommended.

EN 1992-1-1 (2004) (Design of Concrete Structures Part 1-1: General rules and rules for buildings) gives a general basis for the design of structures in plain, reinforced and pre-stressed concrete made with normal and light weight aggregates together with specific rules for provided guidelines for related aspects of reliability. This code has detailed partial factors for actions, material properties and resistances. buildings but with no attention on load conversion factors.

EN1993 1-1 (2005) (Design of Steel Structures- Part 1-1: General rules and rules for buildings) applies to the design of buildings and civil engineering works in steel. This code is concerned only with the requirements for resistance, serviceability, durability and fire resistance of steel structures. A thorough view into this code reveals the absence of load conversion factors as they have not been considered.

EN1997-1 (2004) (Eurocode 7: Geotechnical Design: Part 1. General rules) is applied to the geotechnical aspects of the design of buildings and civil engineering works. The code recommends serviceability limit state design loads to be used when calculating foundation displacement for comparison with serviceability criteria. Furthermore, the serviceability of strip and raft foundations shall be checked assuming serviceability limit state loading and a distribution of bearing pressure corresponding to the deformation of the foundation and the ground. Here, both ultimate and serviceability limit states are to be considered in geotechnical design and construction. Partial factors on actions and effects of actions are given in Tables A1 and A2 while soil parameters are given in Table A2 and A4 of the code. However, converting ultimate limit state loads to service loads have not been discussed, likewise conversion factors specified for such purposes.

Canadian Standards Association, CSA Standard (2004) (A23.3 - 04: Design of concrete structures) specifies requirements in accordance with the national building code of Canada, for the design and strength evaluation of structures of reinforced and pre-stressed concrete, plain concrete elements, and special structures such as parking structures, arches, tanks, reservoirs, bins and silos, towers, water towers, blast-resistant structures and chimneys. However, conversion factors have not been discussed or specified in this code.

Australian Standards – New Zealand Standards (2000) (AS-NZS 1170-2 Structural design actions – Part 0 - General Principles) specifies general procedures and criteria for structural design of a building or structure in limit states format. Conversion factors have not been considered in this code.

Indian Standards 456 (2000) (Plain and reinforced concrete - code of practice) deals with the general use of plain and reinforced concrete. This code specifies details and procedures for design of footings, including load factor values for load combination purposes but has not considered conversion factors.

Japanese Society of Civil Engineers, JSCE (2010) (Standard specification for concrete structures – 2007 "Design") provides principles for structural design and verification of performances of all concrete structures, including those made with reinforced concrete, pre-stressed concrete and steel concrete composites as well as the prerequisites for verification and structural details. This specifies 1.0 as the load factor to be taken for every kind of serviceability limit state. However, conversion factors or alternative procedures for computing service loads have not been included or mentioned.

Hong Kong Building Department (2013) Code of practice for structural use of concrete 2013 provides recommendations for the design, construction and quality control of reinforced and pre-stressed concrete buildings and structures where concrete is made of normal weight concrete. Load factors and load combinations have been specified in this code, but conversion factors have not been considered.

Hong Kong Building Department (2011) Code of Practice for Structural use of Steel 2011 states that serviceability loads be taken as the specified characteristic loads, i.e., un-factored and also gives value of load factor for serviceability calculation as 1.0. Like others, conversion factors have not been considered in this code.

American Concrete Institute ACI 318-11 (2011) Building Code Requirement for Structural Concrete and Commentary covers materials, design, and construction of structural concrete used in buildings and where applicable in non-building structures. It also covers the strength evaluation of existing concrete structures, but conversion factors are not covered in this code.

American Institute of Steel Construction (2016) ANSI/AISC 303-16 Code of Standard Practice for Steel Buildings and Bridges set forth criteria for the trade practices involved in steel buildings, bridges and other structures, where other structures are defined as those structures designed, fabricated and erected in a manner similar to buildings, with building-like vertical and lateral force-resisting elements. However, conversion factors have not been discussed in this code.

New Zealand Standard Council (2006) NZS 3101 Part 1:2006 Concrete Structures Standard – The Design of Concrete Structures sets out minimum requirements for the design of reinforced and pre-stressed concrete structures. This standard also considers and specifies the use of service loads for determination of the base area of footing or number and arrangement of piles to ensure that overall and differential settlement criteria are met at the serviceability limit state. However, this standard has also not considered load conversion factors.

Hong Kong Building Department (2004) Code of Practice for Foundations is prepared on the basis of being 'deemed-to-satisfy' the Building (Construction) Regulations as far as the design and construction of foundations are concerned. Departure from the requirements and recommendations of this Code or the use of other standards or codes of practice for design of foundations, according to this code, may require demonstration of the compliance with the provisions of the Building (Construction) Regulations and is intended for local use only. This code states that the foundation of a building shall be designed to carry the working load with adequate factor of safety. Procedures or parameters required for the computation of the service loads have not been detailed in this code. Load conversion factors have also not been considered here.

DISCUSSION AND CONCLUSION

The reviews above show that both ultimate loads and service loads are required for building foundation design, the service loads basically required determining the base area of footings or number and arrangement of piles. This is clearly stated in the codes.

For loads aggregated at the ultimate limit state, conversion factors are employed to convert them to service loads, to save time and cumbersomeness of the computation process. The conversion factor is a ratio of the ultimate load to the service load, according to BS 5950 Part 1 (2000). AC 193 defines it as a weighted average of the load factors for a given governing loads combination. The ratio concept is applicable when loads are aggregated but that of AC 193 applies when dead loads and live loads are collated separately.

The value of conversion factors given in the reviewed works are not specific and are inconclusive as they are either not definite or a product of experience. For instance, the value 1.46 given by Oyenuga (2001) was discovered through experience and the call for caution in the application of this factor suggests other unknown issues exist which might hamper outcomes of computations if not known or controlled. On the other hand, BS 5950 Part 1 (2000) is not specific on the value of load conversion factor as the value it specifies cannot be traced to any particular live load. Although the range of values it specifies seems realistic, the values cannot be readily applied. Also, these values can be assumed to be applicable to steel structures but not reinforced concrete structures. Further, the load conversion factor values are largely influenced by the relative magnitude of the different types of loads, which also varies with the relative magnitude of the different types of loads.

Load conversion factors address real life issues. Since they have to do with real life situations, obtaining or generating them will involve simulation and modelling. Structural models can be developed and simulated to determine the behaviour of the structure such as loads and load distribution, bending moments, shear forces, etc. Loads aggregated at both the ultimate limit and the serviceability limit states are collated or live loads and dead loads aggregated separately are collated. The concepts highlighted in BS 5950 Part 1 (2000) or International Code Council – Evaluation Service (2012) in AC 193 as well as those by Quimby (2008) can be employed to compute the respective load conversion factors.

It is evident from the review that little has been done so far on load conversion factors. Also, the non-inclusion of this factor in most major concrete and steel design codes and standards suggests that it has not been considered a relevant design parameter. However, in view of its relevance and significance in serviceability limit state load computation, there is the need to seek for or evolve appropriate and suitable load conversion factors that will be widely applicable and acceptable. This step, when taken, will not only address the shortcomings of the existing conversion factors but will also assist greatly in maintaining an appropriate and suitable balance between economy and safety in foundation design.

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