

Simplified Analysis and Design of Bored Cast in-situ Reinforced Concrete Cantilever Sheet Pile Walls in Clayey Soils

Isam G. Jardaneh, Ph.D., P.E.

Civil Engineering Department, Faculty of Engineering,

An-Najah National University, Nablus, Palestine.

Abstract: This paper considers the bored cast in-situ reinforced concrete cantilever sheet pile wall as one of many excavation support systems. There is no specific design and analysis procedure for such excavation support system and most designers rely on experience rather than on engineering methods. The aim of this paper is to present a simplified analysis and to design a method to the proposed excavation support system in clayey soil, which will provide valuable design parameters, such as, penetration depth of the sheet pile, maximum bending moment and shear force, and maximum deflection at the top of the cantilever sheet pile for various arrangements of bored piles that form sheet piling.

Key Words: Excavation Support Systems, Bored Cast in-situ Sheet Piles, Maximum Bending Moment, Penetration Depth, Deflection of Sheet Pile.

تحليل وتصميم مبسط للجدران الداعمة الكابولية المكونة من أوتاد مصبوبة في الموقع في التربة الطينية

ملخص: الحفريات في التربة أو الصخر هي من أهم عناصر بناء المنشآت تحت سطح الأرض. إن هذه الحفريات بحاجة إلى نظام دعم مناسب؛ وبالرغم من أهمية هذه العملية إلا أن معظم المصممين والمقاولين لا يعرفون إلا القليل عن تحليلها وتصميمها ويعتمدون بشكل أساسي على الخبرة السابقة. يهدف هذا البحث إلى وضع تحليل مبسط للأوتاد الكابولية المستخدمة لدعم دفع التربة الطينية الجانبي وذلك لتصميم هذا النظام. إن هذا البحث يعطي مقدار عمق اختراق الأوتاد للتربة والقيم القصوى لكل من قوى العزم والقص وكذلك القيمة الكبرى للإزاحة الجانبية. فبذلك يقدم هذا البحث طريقة مبسطة وسهلة لمهندسي التصميم بدون الحاجة لفهم التحليل الدقيق والمعدّد لنظام الدعم المقترح.

1. Introduction

Generally, two main types of excavations are available: open excavation and braced excavation. Open excavations do not require bracing to support the soil. When it is uneconomical, illegal, or impossible to use open excavations,

bracing is employed to support the soil. Many bracing systems are available, the most commonly used are soldier beams and lagging, sheet piles, slurry-walls, bored cast in-situ sheet pile wall, cofferdam, soil nailing, soil grouting, and soil freezing (Long, 2001, Simpson, 1992, Mitchell and Christopher, 1990, O'Rourke and Jones, 1990, Lambe, 1970).

For difficult sites and soils bored cast in-situ reinforced concrete cantilever sheet pile walls is a common practice (Thasnananipan et al., 1998, Brooks and Spencer, 1992). However, there is no simple method for analyzing and designing such excavation support system (Osman, and Bolton, 2004, Chini, and Genauer, 1996). Very sophisticated analysis methods are sometimes used, such as, finite element methods, boundary element methods, and centrifuge methods (Leung et al., 2000, Goh et al., 1997). However, such analysis methods are very expensive and require many parameters that are difficult to be determined (Poulos and Chen, 1997). Such method is mainly used for research purposes.

Analysis methods for bored cast in-situ sheet pile can be subdivided into four basic categories, as described by Stewart et al. (1994):

1. Empirical methods based upon field observations and the results of laboratory experiments.
2. Pressure-based methods, where a pressure distribution acting against the piles is estimated in a relatively simple manner.
3. Displacement-based methods, where the distribution of lateral soil displacement with depth is input.
4. Advanced techniques methods, such as finite element method, boundary element method, and centrifuge modeling.

The method used in this paper is a classical one using software called SPW911 (Lindhahl and Warrington, 2007). This method falls within the second option of the above categories. It is based on the pressure model presented by CIRIA Report 104, published in 1984 (Padfield and Mair, 1984).

This paper will present a simplified analysis and design of reinforced concrete bored cast in-situ cantilever sheet pile walls in clayey soils. From analysis point of view, it will provide penetration depth, maximum bending moment, maximum shear force, and deflection at the top of the sheet pile (maximum deflection). These outputs are given for different arrangements of piles. In addition, this paper will provide a hint for selecting (design) arrangement to provide safe case.

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2. Importance and Objectives of the Study

Four common methods are available locally as excavation systems (Jardaneh, 2006), which are: open cuts, gravity and semi-gravity retaining walls, cantilever retaining walls, and bored cast in-situ reinforced concrete piles. The collected data indicated that there were no analysis and design procedures or specific guidelines for the construction of excavation support systems (Jardaneh, 2006). However, most designers tended to rely on their experience and used common methods of design procedures for excavation support as permanent structures, like retaining walls and sheet piles. Codes and project specifications simply required the designer to provide safe access and support for excavations.

The main objective of this paper is to present a simplified analysis and design of reinforced concrete bored cast in-situ cantilever sheet pile walls in clayey soils. The presented analysis method will provide the designer, for different pile diameters and pile arrangement, i.e., spacing between the bored cast in-situ piles, with the following valuable data:

- Value of maximum bending moment
- Value of maximum shear force
- Value of maximum deflection at the top of the cantilever sheet pile
- Penetration depth of the sheet pile, hence, the total length of the sheet pile can be determined.

3. Methodology

The methodology used to fulfill the above objectives is through:

- a. Using special program called SPW911 (Lindahl and Warrington, 2007) for analysis of the excavation system proposed in this study. This program is based on classical analysis method as presented in CIRIA Report 104 (Padfield and Mair, 1984);
- b. Selecting arrangements (rows and spacing) of bored cast in-situ piles to form sheet pile wall;
- c. Choosing soil properties and parameters to provide parametric study;
- d. Considering several excavations depths; and,
- e. Developing curves to make the analysis simple and help in the design process.

4. Assumption Regarding Design Parameters

4.1 Excavated Soil Characteristics

Assumptions regarding such soil from practical point of view are as follows: to simplify the problem, the soil is assumed having constant undrained cohesion (C_u) and unit weight all over the entire depth, and hence, the angle of internal friction (ϕ) is equal zero. The reason for using undrained cohesion is the easy way to get this parameter through unconfined compression test, since undrained cohesion is equal one-half the value of unconfined compressive strength (q_c), i.e. $C_u = \frac{1}{2} q_c$. In addition to that unconfined compressive strength provides high factor of safety. Adhesion between soil and piles (δ) is assumed = 0.0 and this also provides safer case. It is worth mentioning that since $\delta = 0$, then Rankine and Coulomb passive and active lateral earth pressures are the same. For layered soil weighted average undrained cohesion should be determined. Unit weight is assumed constant and equal = 17 kN/m^3 (this may be considered reasonable for firm to stiff silty clay soils). Varying undrained cohesion (C_u) is taken as 50, 70, 90, and 110 kN/m^2 . These values covers all possible clay parameters in our region (Jardaneh, 2006).

The excavation depths that are covered in this paper are 5, 7, 9, and 11 meters. The minimum excavation is 5 m, below this depth; it is not feasible to use the suggested excavation support method. Cheaper and simpler support system may solve the problem. For excavation greater than 11 m, it is uneconomical and very high deflection is expected, so this type of excavation support is unsuitable. Water pressure was not taken into consideration in this paper, since water table, in our region is very deep and has no effect on the suggested sheet pile (Jardaneh, 2006).

4.2 Sheet Pile Characteristics

The sheet pile is made up of different arrangements of bored cast in-situ circular like reinforced concrete cantilever piles. Typical reinforcement provided for this type of piles is those provided for short columns. The compressive strength of concrete based on cube compression test is at least 25 MN/mm^2 . The arrangements of piles to form sheet piles are as follows:

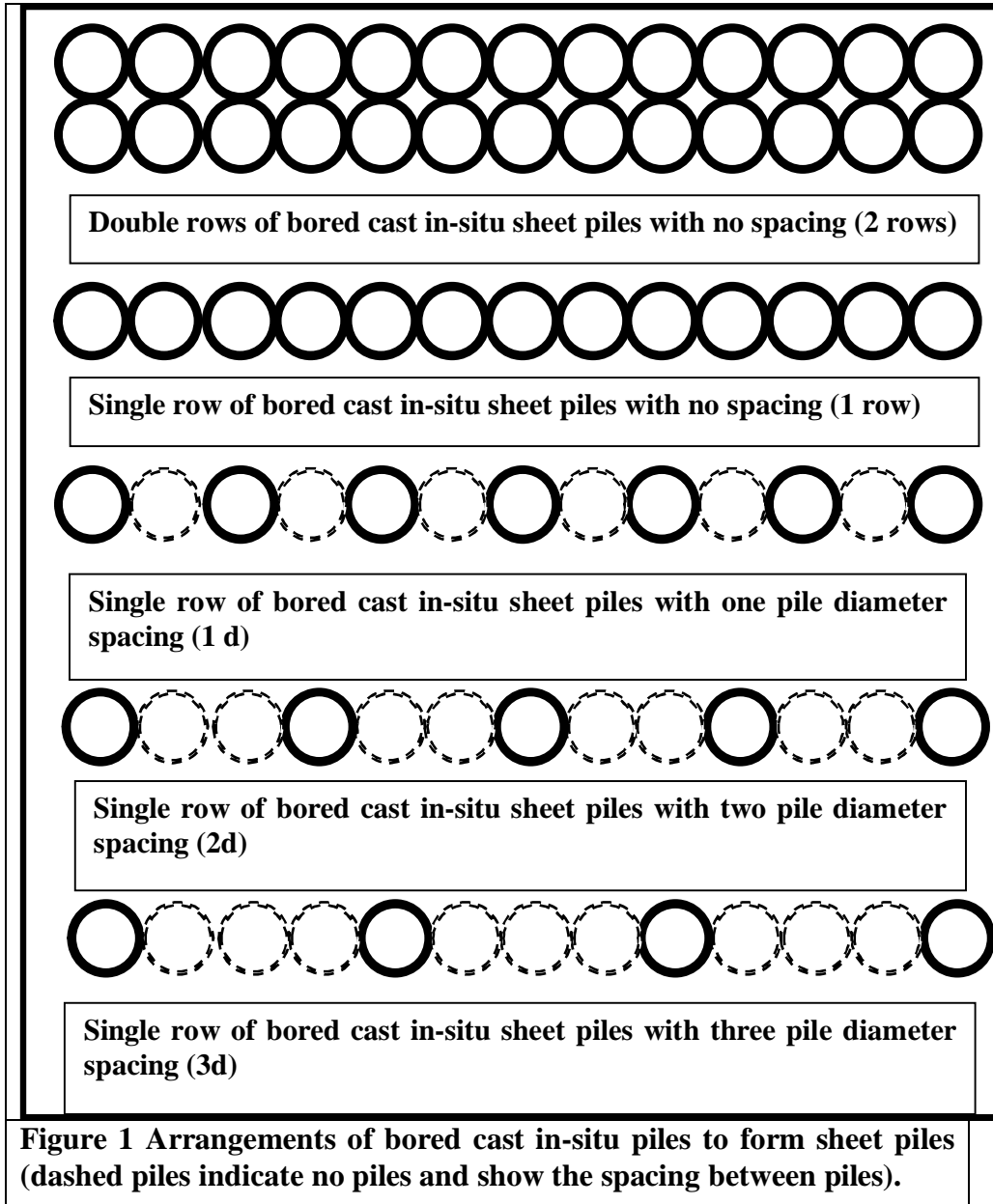
- 1.** double rows of piles with no spacing between piles
- 2.** single row of piles with no spacing between piles
- 3.** single row of piles with one pile diameter spacing
- 4.** single row of piles with two pile diameter spacing
- 5.** single row of piles with three pile diameter spacing

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Figure 1 illustrates the above arrangements. This arrangement covers, from practical point of view, all possible pile arrangement that may be used as sheet piles.

Bending moment and shear force capacities for different pile arrangements and diameters are calculated and shown in Figures 2 and 3 below. These capacities are calculated based on minimum reinforcement and compressive strength of concrete.

It is worth mentioning that the area and moment of inertial is calculated based on the arrangement of the piles. That is to say it is found for number of piles per meter run of the sheet pile.



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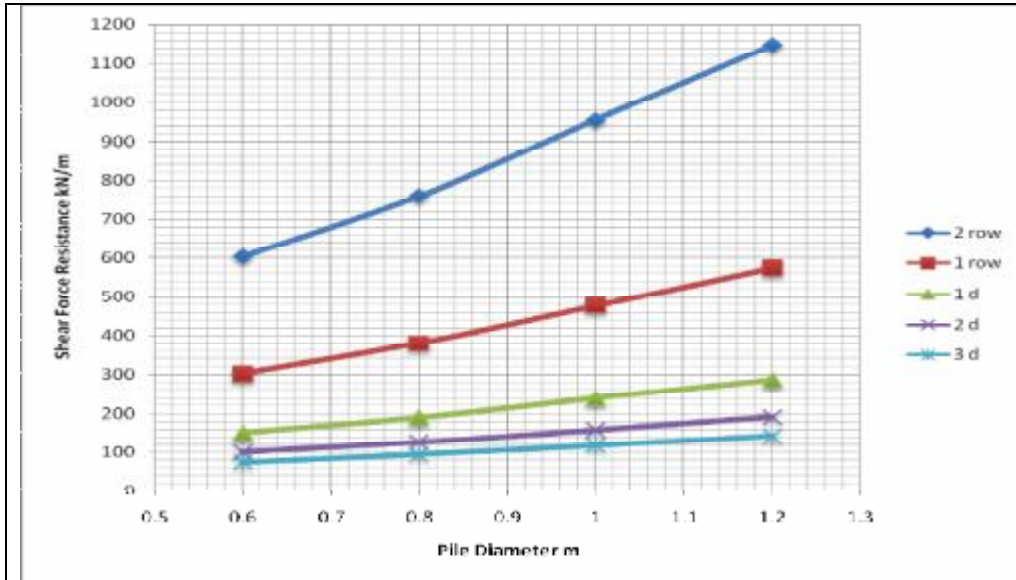


Figure 2 Shear force capacity for different pile diameters and arrangements.

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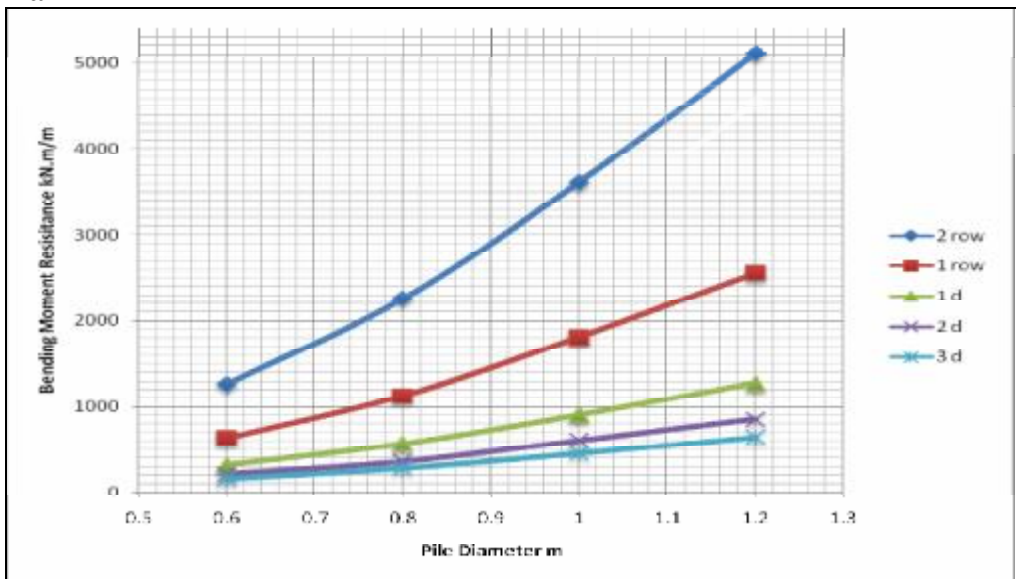


Figure 3 Bending moment capacities for different pile diameters and arrangements.

5. Sheet Pile Wall Software (SPW911)

The analysis was carried out in this paper through software called SPW911, which is based on the classical method of analysis of sheet pile (Lindahl and Warrington, 2007). This software was introduced by Pile Buck in 2001, and then since, it has become an indispensable tool for the analysis of sheet pile walls. The aim of this software is to provide pressure distribution behind the sheet pile, maximum shear force, maximum bending moment, and maximum deflection along the sheet pile. The latest version of this program contains new features, such as, improved pressure model, accurate calculation for shear force, bending moment, and deflection, allows entering the factor of safety as required by some codes, and gives new alerts for excessive deflection.

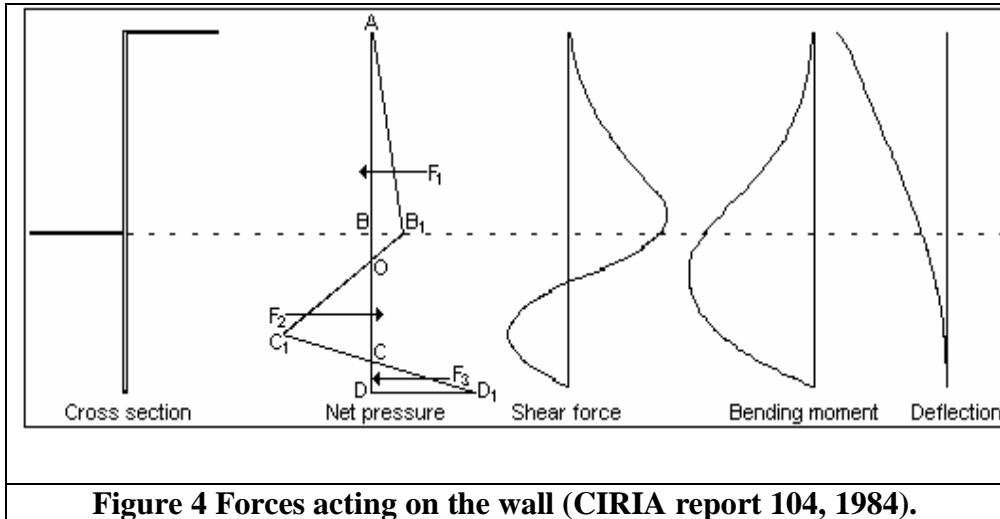
The classical method used by this software is a pressure-based method, which was adopted from the pressure model presented in CIRIA Report 104, 1984 (Padfield and Mair, 1984) and presented in British Steel Piling Handbook, 1997, and adopted by British Standard BS8002: 1991. This method shows excellent prediction results according to Day, 2001. The net pressure is calculated using Rankine or Coulomb pressure model by calculating the active and passive pressure that can be found in any soil mechanics text book (since $\delta = 0$, then Rankine and Coulomb active and passive lateral earth pressures are the same). The forces acting on the wall can be represented as shown in Figure 4. Each force is assumed to act through the centre of gravity of the given areas:

F1 = area AOB₁ = total net active pressure

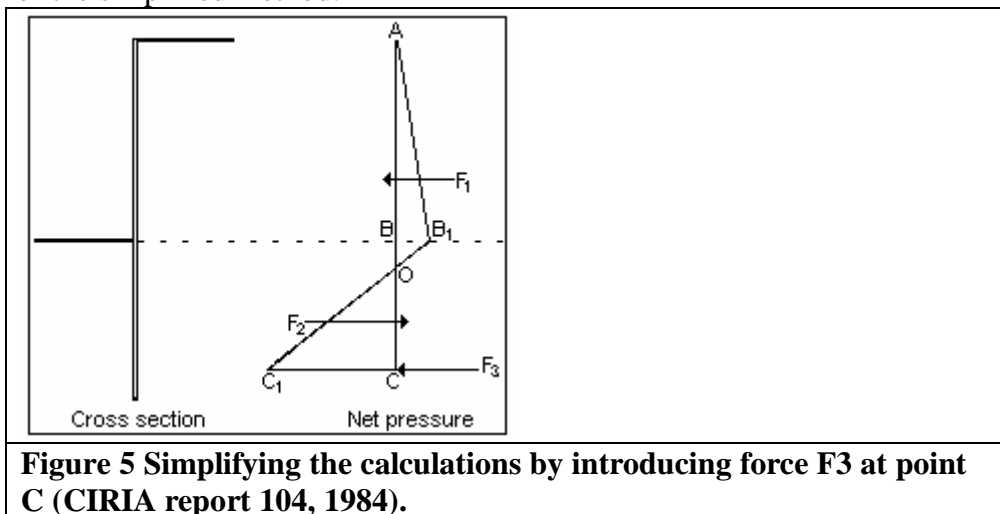
F2 = area OCC₁ = total net passive pressure

F3 = area CDD₁ = total net passive pressure required to fix toe of wall

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To simplify the calculations, line C_1CD_1 may be considered to be horizontal, and force F_3 to act at point C as shown in Figure 5. A correction factor is applied to the calculated toe to compensate for this approximation. The depth OC is such that the moments of forces F_1 and F_2 about F_3 (i.e. point C) are in equilibrium. The calculated toe is increased by $0.2 \times OC$, to compensate for the simplified method.



The factor of safety against rotational failure for cantilevered sheet pile is given by the ratio of the restoring moments about point C to the disturbing moments about point C. The factor of safety used in the design of the suggested excavation support system is 2. Sheet deflections are calculated by finding the bending moment, and then, solving the second order differential equation.

It is recommended that minimum standard surcharge of 10 kN/m^2 be applied to the surface of the retained soil in the design of all retaining walls (Lindahl and Warrington, 2007). However, in this paper, the surcharge load was taken 20 kN/m^2 ; to take into account, additional surcharge loading, such as, vehicles movement, fill materials, etc.

6. Results of Analysis

The results are found and curves are plotted to form the basis for analysis and design of the proposed excavation support system. The results are shown in Figures 6, 7, 8, 9, 10, 11, and 12. Figure 6 shows the penetration depth required versus excavation depth for different values of undrained cohesion of the silty clay. Since the structure here is cantilever (determinant structure), then, the penetration depth is irrelevant to sheet pile properties such as pile diameter and arrangement (modulus of elasticity, area and moment of inertia per length of the sheet). Figure 7 shows the value of maximum value of bending moment versus excavation depth for different values of undrained cohesion. Figure 8 shows the value of maximum shear force versus excavation depth. It is worth mentioning that the value of maximum shear force is independent of undrained cohesion.

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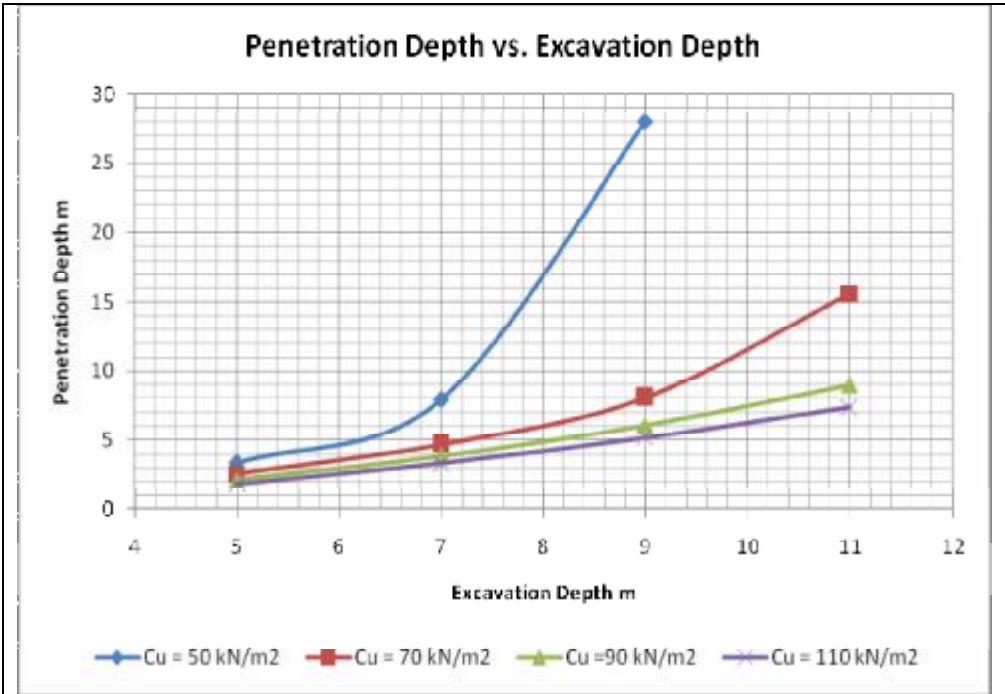


Figure 6 Penetration depths versus excavation depth for various values of undrained cohesion.

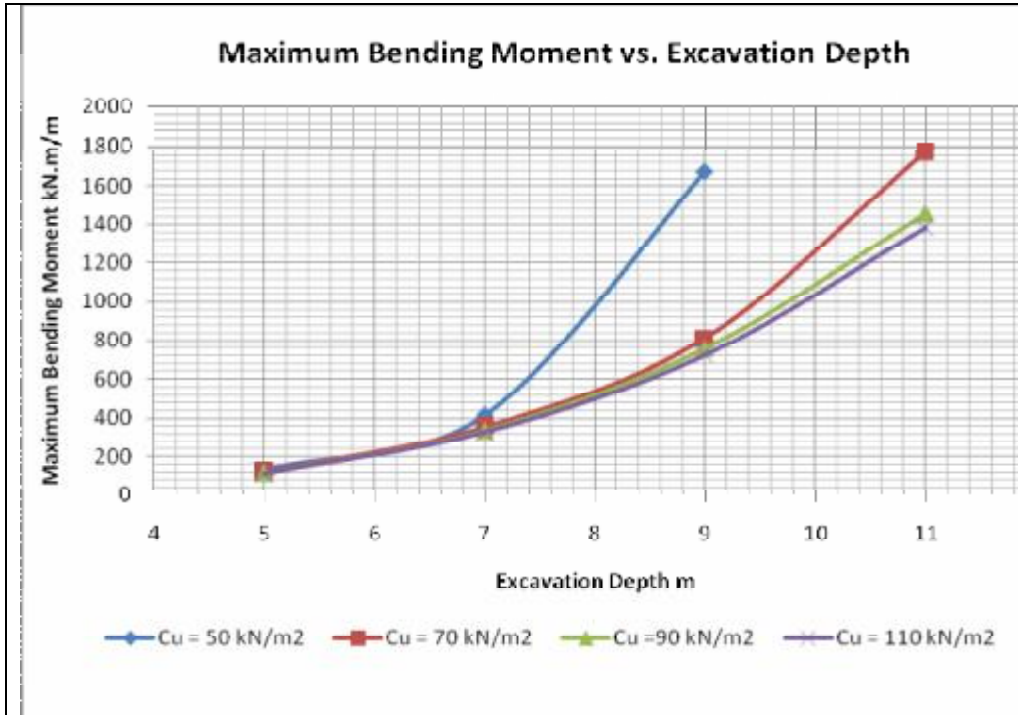


Figure 7 Maximum bending moment versus excavation depth for different values of undrained cohesion.

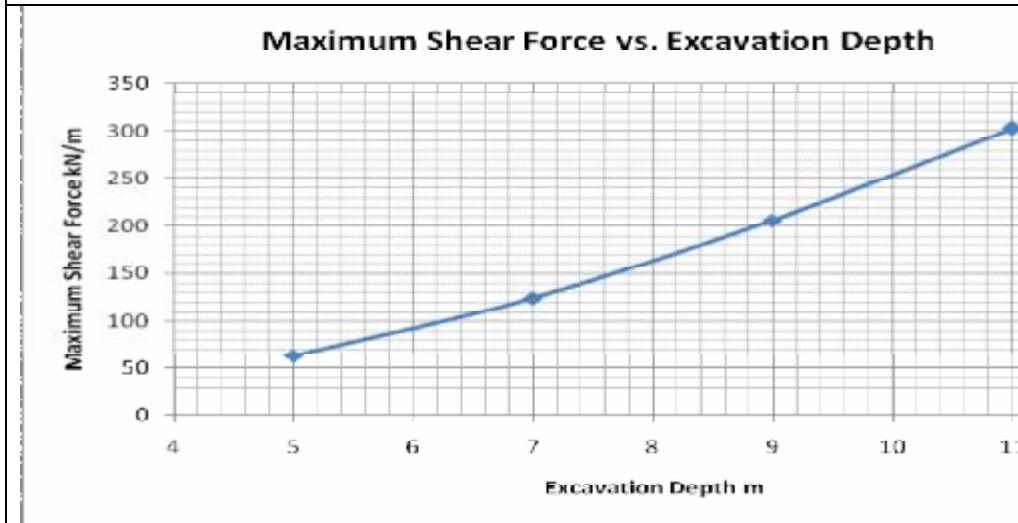
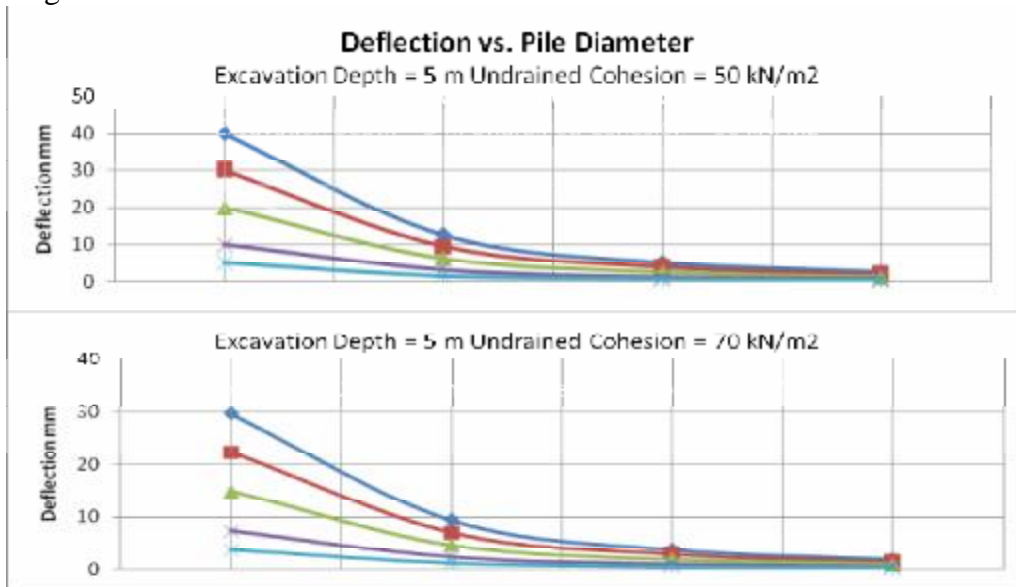


Figure 8 Maximum shear force versus excavation depth.

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Finally, the maximum deflection, which occurs at the top of the cantilever sheet pile, is presented in Figures 9, 10, 11, and 12. They show the deflection versus pile diameter for excavation depth and different values of undrained cohesion. The value of deflection depends on the sheet pile properties and arrangement, such as modulus of elasticity, area and moment of inertia per length of the sheet.



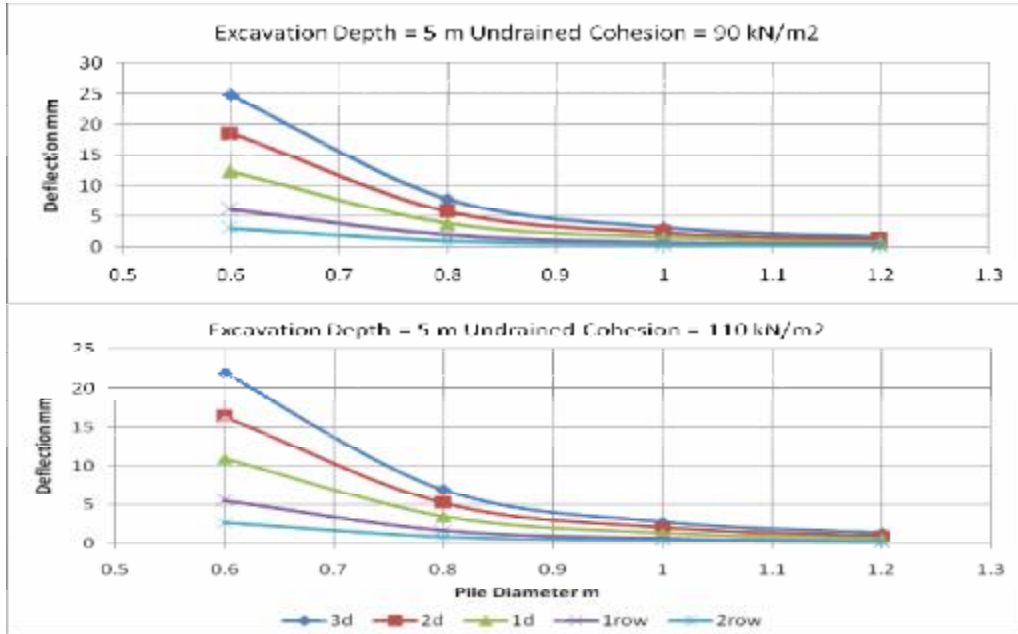
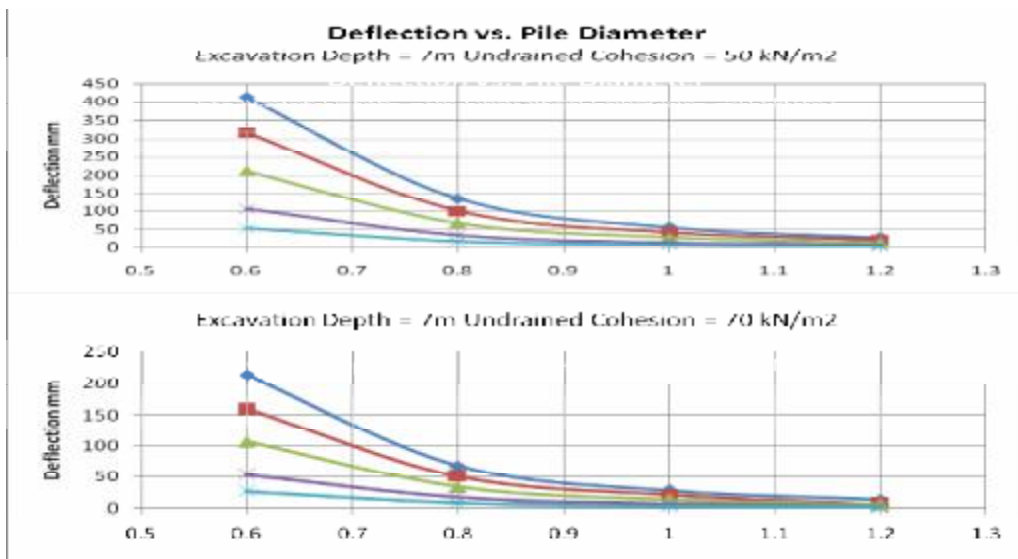


Figure 9 Deflection versus pile diameter for various values of undrained cohesion for excavation depth = 5 m.



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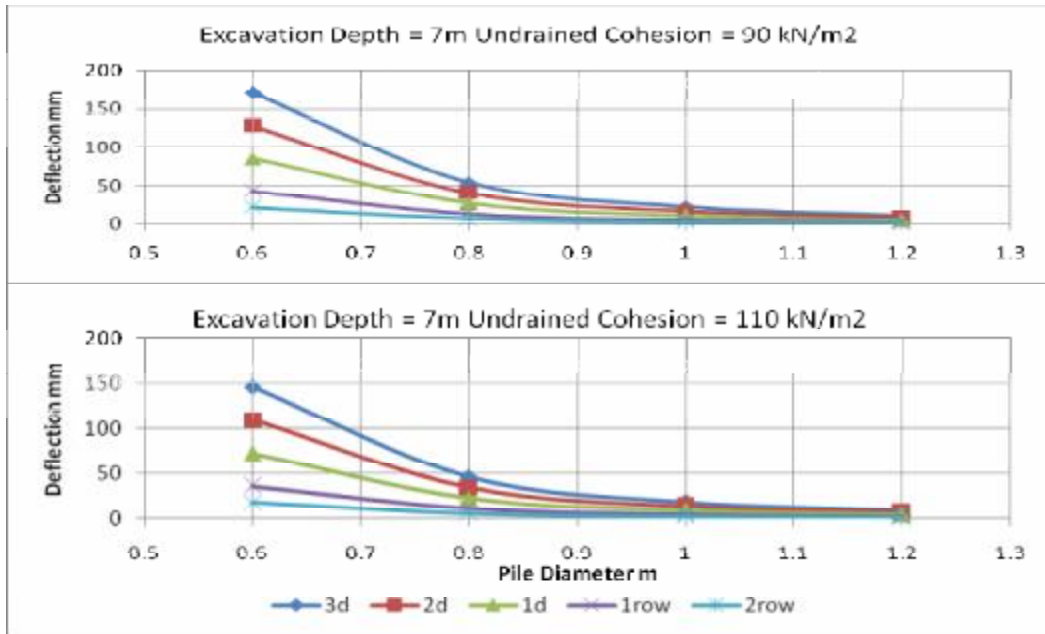
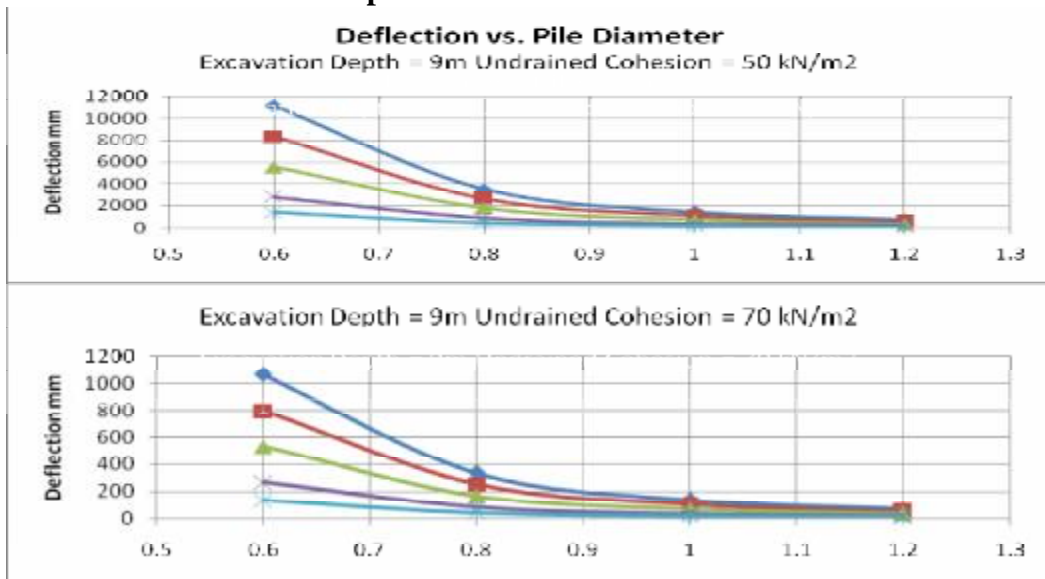


Figure 10 Deflection versus pile diameter for various values of undrained cohesion for excavation depth = 7 m.



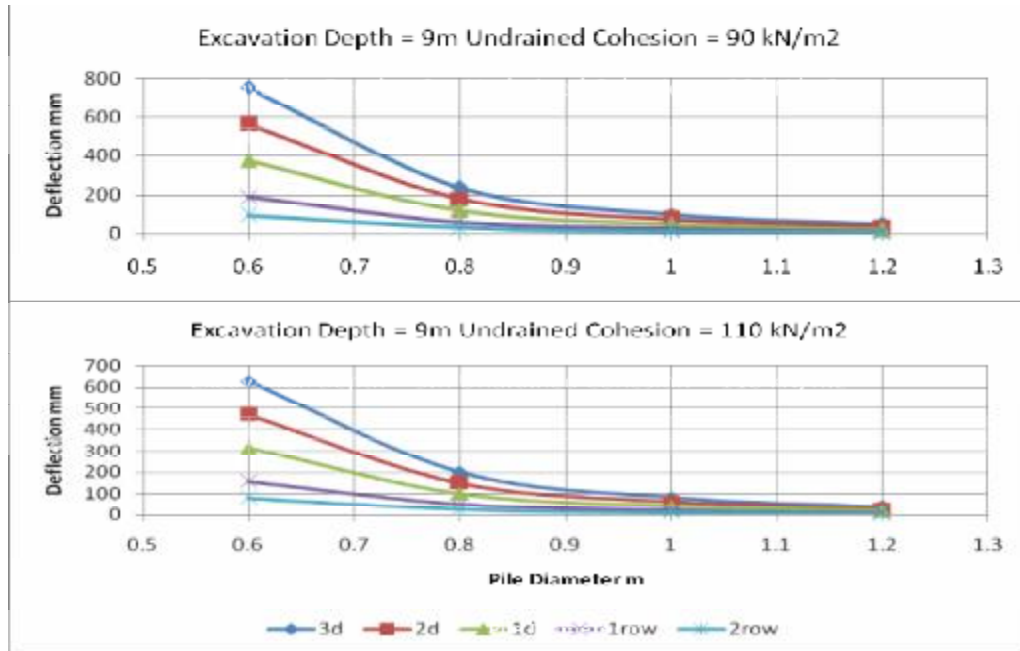


Figure 11 Deflection versus pile diameter for various values of undrained cohesion for excavation depth = 9 m.

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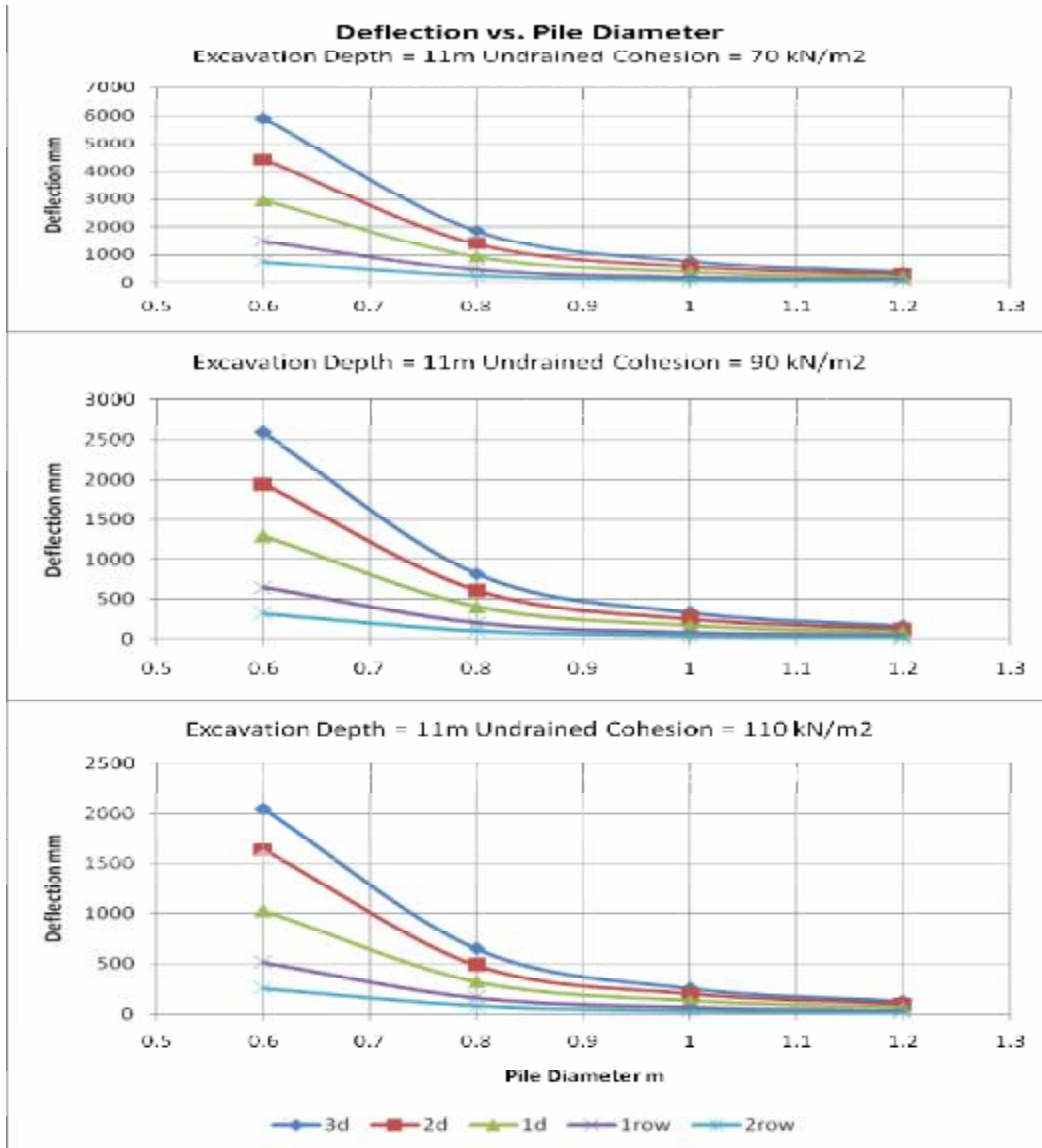


Figure 12 Deflection versus pile diameter for various values of undrained cohesion for excavation depth = 11 m.

6.1 Using the Results for Analysis and Design

To use the curves for analysis and design, first get the undrained cohesion (C_u) of the clayey soil from unconfined compressive strength. Weighted average should be calculated if the soil is not uniform and having varying undrained cohesion. Knowing the required excavation depth, then the penetration depth can be determined from Figure 6, and hence, the total height of sheet pile can be determined. Figures 7 and 8 provide the maximum bending moment and shear force. Now, according to the values of bending moment and shear force get the diameter and arrangement of the piles to form the sheet pile from Figures 2 and 3. Check for the given arrangement the maximum deflection at the top of sheet pile. If it is not acceptable, then re-select another arrangement with higher bending moment and shear force capacities, and re-check the deflection till acceptable settlement is found.

It is worth mentioning that, the discussed excavation support system (bored cast in-situ reinforced concrete cantilever sheet pile) is suitable for intermediate heights up to 9.0 meters.

7. Conclusions

This paper provides a simplified analysis and design procedure for bored cast in-situ reinforced concrete cantilever sheet piles in clayey soil. The analysis is based on classical method as recommended by CIRIA report 104; however, such analysis provides good agreement as shown by many researchers using advanced and complicated analysis such as finite element method. This paper provides a simple method to get penetration depth, maximum deflection, maximum bending moment and shear force.

The sheet pile wall is assumed to be constructed from different arrangements of bored cast in-situ reinforced concrete cantilever piles. These arrangements cover all possible pile arrangement to be used as sheet piles from practical point of view. This type of support system is good for intermediate height up to 9.0 m.

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