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Fundamentals of Ground Improvement Engineering

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List of Chapters

Chapter 1 Introduction to Ground Improvement Engineering (figures not included)

1.1. Introduction

Ground modification in the constructed environment is not a new idea. For instance, the method of wattle and daub has been used for thousands of years to provide tensile reinforcement to clayey materials in buildings. The process of adding straw to clay and baking it in the sun improved the strength properties of the clay creating a building material that has been used for thousands of years. In another ancient application, the Romans used timber as a base layer for roads. In modern times, inclusions (such as geogrids and geotextiles) are commonly employed for ground improvement. Similarly, the addition of lime to clay (a chemical admixture in modern terminology) has long been used to create a weak binder in stone foundations. The Roman road, via Appia, now in modern day Italy, is the earliest known example of the use of lime in ground improvement engineering (Berechman 2003).

The terms *ground improvement*, *ground modification*, and similar terms are lexicon of the late 20th century. The first conference on the subject was "Placement and Improvement of Soil to Support Structures" and was held in Cambridge, Massachusetts, in 1968, sponsored by the Division of Soil Mechanics and Foundation Engineering of the American Society of Civil Engineers (ASCE 1968). The first comprehensive textbook on the subject was by Hausmann (1991). University courses on the subject began about the same time. In many ways, ground improvement engineering is a relatively new field within geotechnical engineering. New developments are occurring at a rapid pace and no doubt will have occurred throughout the life of this book. Thus, this book focuses on fundamentals, enabling the user to understand and adapt to the latest ground improvement developments.

How might ground modification/improvement be defined? In the Proceedings on the Conference on Soil Improvement (ASCE 1978), the introduction succinctly states that one of the alternatives available when poor soil conditions are encountered is "treat the soil to improve its properties." Moseley and Kirsch (2004) in the second edition of their book, Ground Improvement, note that "All ground improvement techniques see to improve those soil characteristics that match the desired results of a project, such as an increase in density and shear strength to aid problems of stability, the reduction of soil compressibility, influencing permeability to reduce and control groundwater flow or to increase the rate of consolidation, or to improve soil homogeneity." Shaefer et al. (2017) define ground modification as "… the alteration of site foundation conditions or project earth structures to provide better performance under design and/or operational loading conditions." For the purposes of this book, ground improvement is defined as application of construction means and methods to improve the properties of soil.

Note that some improvements are of the first order. For example, compaction will increase the density of a soil. However, density increases can lead to second order effects such as increased strength and reduced compressibility. Finally, these second order improvements can result third order effects such as increased bearing capacity and reduced settlement and/or improved liquefaction resistance. By beginning with the fundamentals of ground improvement engineering, the text is designed to provide and understanding of both the fundamental first order effects as well as those second and third order effects that are often the actual desired outcome of the application of ground improvement. As there are many definitions of ground improvement and further much gray area within each definition, the authors used this definition as a guide to define the scope of this book.

Finally, for the purposes of the selection of the content in this book, the authors use the term ground improvement rather than ground modification. Ground modification is a neutral term meaning the modification could either improve or worsen the ground whereas ground improvement is unambiguous.

Prior to in depth study of ground improvement, what are alternatives to ground improvement? Imagine a site where the subsurface conditions are not suitable for the anticipated project. While ground improvement is the option to be considered in detail in this book, what are the alternatives? Some common alternatives to the application of ground improvement include:

- **Avoid the site or area:** There are many circumstances where the owner/developer has options regarding the location of the proposed facility and finding an alternative site or a different area of the same site is a viable option.
- **Remove and replace:** If the unsuitable materials are limited in aerial and/or vertical extent, the best (and most economical) option may be to simply excavate the unsuitable soils and replace them with more suitable materials having more predictable properties, such as crushed stone. This is a commonly chosen alternative when localized fill is encountered.
- **Transfer load to deeper strata:** The use of deep foundations, such as piles or drilled shafts, has long been the option of choice in locations where unsuitable bearing materials are present near the ground surface. Deep foundations affect load transfer though the use of stiff structural members placed between the structure and competent bearing materials found at deeper depths. Although significantly more sophisticated today, this technique has existed for centuries with ample evidence including ancient Roman bridges supported on timber piles.
- **Design structure accordingly:** Some sites and structures, in combination, may lend themselves to structural redesign to accommodate the site conditions. For instance, it may be possible to stiffen the structure to redistribute stresses within the structure and minimize differential movement. In a specific application, sinkhole prone areas such as solution prone geologic settings, grade beams can be used to connect spread footings in order to redistribute loads in case of loss of support beneath any single footing. Likewise, structures can incorporate construction joints, allowing some differential settlement without causing distress.

1.2 Improvements in Soil Behavior

Ground improvement may be viewed from the perspective of system performance. For example, it may be necessary to improve the ground to increase the allowable bearing value of a footing supported on the soils beneath a structure. From the system perspective, ground improvement alternatives would be evaluated for their ability to increase bearing capacity and decrease settlement, i.e. increase the allowable bearing value. More precisely, the allowable bearing value can be increased by:

1. Increasing the stiffness of the soil (decreases settlement)
2. Increasing the shear strength of the soil (increases bearing capacity)
3. Decreasing soil property variability (decreases differential settlement).

Densifying granular materials or consolidating cohesive materials can increase soil strength and stiffness.

Using these definitions, there are many ways ground improvement can be viewed. For the purposes of understanding ground improvement, this text will focus on a fundamental understanding of the interactions between ground improvement techniques and the resulting changes in soil and/or soil system behavior. This text also provides insight into the means and methods used by contractors to implement ground improvement techniques with most of the chapters and information segmented by construction techniques.

In this chapter, it is useful to articulate the improvements in soil behavior that may result from the ground improvement methods employed. These fundamental soil behavior characteristics include shear strength, compressibility, hydraulic conductivity, liquefaction potential, shrink and swell behavior, and reduction in variability in any of the aforementioned behavioral characteristics. Details of soil behavior principles related to ground improvement are provided in Chapter 2.

1.2.1 Shear strength

Shear strength is a fundamental engineering property of soils that can be increased through the application of numerous ground improvement techniques. Shear strength is a measure of the soils ability to resist failure under the application of a load that induces shear stresses in the soil. Shear strength can be increased through ground improvement techniques that decrease the void ratio (Chapters 4, 5, and 11), and/or adding a cohesive (cementing) component (Chapter 6 and 7). There are many applications that benefit from improved shear strength including increased bearing capacity, improved slope stability, and reduced liquefaction potential.

Shear strength of soils is a sophisticated concept. There are entire texts devoted solely to this topic. Unconfined compression tests (see Figure 1.1) are a common means to quantitatively judge the benefit of ground improvement efforts. For some projects, more sophisticated testing may be needed. Principles of shear strength, both drained and undrained, are reviewed in Chapter 2.

1.2.2 Compressibility

Soil stiffness is a measure of the deformation of soils associated with the application of a load. Compressibility is not a unique value, since it depends on the nature of the load application and the initial stress state of the soil. The soil stiffness can be increased, i.e. decreased compressibility, through ground improvement techniques that reduce void ratio or add a cohesive or cementing component. Cohesive soil stiffness can be increased by compaction (Chapter 4) and consolidation (Chapter 5). Granular soil stiffness is generally increased by densification (Chapter 4). Cohesive and granular material compressibility can also be reduced via increasing cohesiveness through soil mixing (Chapter 6) or grouting (Chapter 7).

One of the most well-known cases of excessive deformation (aka settlement) is the campanile (bell tower) in Pisa (see Figure 1.2), aka the "Leaning Tower of Pisa". Differential movement of the ground below the tower has been the subject of numerous studies and there have been multiple attempts to stabilize the tower. The differential movement resulting from non-uniform subsurface conditions and is exacerbated by the uneven load application once tilting began. In Figure 1.2, notice the cables extending outward from the left side of the tower. This photograph was taken in 1999 at which time a pulley and counterweight system were in place coupled with lead weights placed directly on the foundation acting as a counterweight employed as an emergency measure to stabilize the tower. Subsequently, ground extraction beneath the high side of the tower proved successful in arresting the movements (Burland, et al. 2009). This famous landmark remains a reminder that controlling deformation and preventing strength failures are two key performance criteria for geotechnical engineering projects.

1.2.3 Hydraulic Conductivity

In most cases, improved ground is ground which is modified to produce a zone of reduced permeability in order to control the detrimental effects of groundwater. For example, flow beneath a dam can lead to soil particle movement (piping) and/or instability. Construction projects also frequently require construction below grade and often below the water table. In these cases, construction dewatering is needed. Ground improvement in such cases might include dewatering, installation of a low permeability vertical barrier (Chapter 8) or reduction in permeability by grouting (Chapter 7).

1.2.4 Liquefaction potential

Loose granular materials below the ground water level can be subject to liquefaction (see Figure 1.3) upon the application of a dynamic load, such as during an earthquake. During shaking, loose granular soil deposits generally decrease in volume (i.e. loose soils densify). If these loose soils are located below the water table, drainage would be needed for the soils to actually densify. This drainage requires sufficient time, which for granular materials, is normally not a problem during static loading. However, during earthquake loading, there is insufficient time for drainage which results in an increase in pore water pressure and a reduction in the effective shear strength of the granular soil. These principles of shear strength and liquefaction potential are presented in more detail in Chapter 2. The most common mitigation of this risk is to densify the soils, which reduces their liquefaction potential. Common tools for densifying granular materials are described in Chapter 4. Other ground improvement techniques to reduce liquefaction potential include ground water control (Chapters 7 and 8) and in situ mixing (Chapter 6).

1.2.5 Shrink/swell behavior

Soils containing smectitic clays are subject to substantial volume changes in response to cycles of wetting and drying. The shrink/swell behavior of these expansive soils can have detrimental effects and can progressively damage a building or cause a retaining wall to fail. Figure 1.4 illustrates road damage due to expansive soils. Understanding clay mineralogy and the resulting expansive behavior (Chapter 2) prior to selecting and designing ground improvement methodologies is important. Ground improvement, through the use of admixtures and in situ mixing (Chapter 6), can minimize the propensity for these materials to change volume with wetting and drying.

1.2.6 Variability

Physical and engineering properties of soils are naturally variable. At times, this variability can affect the performance of a planned structure. For example, if the compressibility varies enough from location to location, excessive differential settlement could be expected. Ground improvement can modify the properties of subsurface materials to provide a more uniform performance. For example, consider the settlement sensitive structure shown in Figure 1.5. Here, the depth to bedrock increased in the downslope direction along the axis of the building. Overlying the bedrock were unconsolidated materials of increasing thickness from one end of the building to the other. Unsurprisingly, concerns with differential settlement arose and a deep foundation system was chosen for the structure (drilled shafts into pinnacled limestone). However, the chosen foundation system was very costly. This short case study serves to illustrate that, under variable site conditions, ground improvement could reduce site variability, permitting an inexpensive shallow foundation system rather than requiring an expensive deep foundation system. For this site, vibro methods (Chapter 5) could have both densified the soils and reduced variability in compressibility across the site. In cases such as this, ground improvement can prove to be significantly less costly and provide performance equivalent to a deep foundation system.

1.3 Overview of Ground Improvement Techniques

Ground improvement principles have certain fundamental mechanistic characteristics that are used to develop a classification system for ground improvement. Accordingly, this book uses four defining principles, in order of increasing complexity:

- Control of water – removal or control of groundwater
- Mechanical modification – rearrangement of soil or water particles
- Modification by additives –addition of chemicals, etc.
- Modification by inclusions or confinement – system behavior modification through rigid or flexible element inclusion or soil confinement

Assigning a particular ground improvement technique to a particular category is imperfect since some techniques possess multiple behavioral characteristics or provide improvement via multiple principles. This results in some techniques having characteristics from more than one category. Nonetheless, such a classification system is useful in understanding how particular techniques work on a fundamental level. Based upon how a given ground modification technique improves the soil, this book is structured according to Figure 1.6.

Some of the important principles, engineering considerations, and construction methods that are the focus of this book are discussed further in the sub-sections below.

1.3.1 Compaction: Shallow Methods

Compaction is the densification of soils at constant water content. Consolidation, in contrast, is differentiated from compaction by the decrease in water content due to the application of load to a saturated soil. Compaction (densification) is achieved through the application of mechanical energy to soil such that the air void volume is decreased, increasing soil density. Surface compaction with equipment, such as the pad foot self-propelled roller pictured in Figure 1.7, has long been used to increase strength, reduce compressibility, and reduce the permeability of soils. Examples of ground improvement techniques that use mechanical energy as the principle means to improve soil behavior include surface compaction, deep dynamic compaction, and rapid impact compaction. These are all surface applications of mechanical energy that that dissipates with depth. In doing so, the mechanical energy causes a rearrangement of the soil structure into a denser configuration. Shallow (surface) methods of compaction for ground improvement are presented in Chapter 4.

1.3.2 Compaction: Deep Methods

Occasionally, the effective depth of surface compaction is insufficient compared to the depth of material targeted for compaction. Here, deep compaction methods, which apply mechanical energy below the surface, are needed. In most cases, deep compaction methods also employ vibration and often involve the addition of stone, grout, or concrete during the process to fill the space created by the densification. Depending upon the details of the process and the contractor completing the work, various names are given to these deep methods. Such names include, but are not limited to, vibro-flotation, vibro-compaction, vibro-replacement, Geopiers®, and rammed aggregate piers® (RAP). For example, Figure 1.8 shows a vibrator used for deep vibro-compaction or vibro-replacement and Figure 1.9 shows the hopper being filled with sand during a vibro-compaction project.

These techniques evolved from work done over 70 years ago by the Keller Company (Kirsch and Kirsch 2010). Deep compaction techniques began to flourish in the 1950's and 1960's. Early projects used large, torpedo-like vibrators operating between 1500 and 3000 rpm and that developed horizontal forces in the range of 100 to 150 kN to effectively compact loose sands. Initially, sand was added at the surface to compensate for the volume change resulting from the densification of the in situ sand. As time passed, bottom feed vibrators were developed for the addition sand or stone, enabling the construction of stone columns. For a more detailed history, particularly European history, of the development of deep vibratory technics, see Kirsch and Kirsch (2010). Deep compaction methods are addressed in Chapter 4.

1.3.3 Soil Mixing and Injection Methods

Soil mixing methods, such as those described in Chapter 6, are methods of ground improvement wherein the soil properties are improved *in situ* via addition of one or more reagents. Injecting or mixing in reagents such as lime, Portland cement, slag cement, or combinations of reagents, can result in increased shear strength, reduced compressibility, and reduced hydraulic conductivity. In addition to understanding the means and methods of soil mixing and injection, an understanding of the mechanisms by which the additives work is critical to the successful choice and use of any particular soil mixing and injection method. For example, reagents can be added in a dry mix method (Figure 1.10) or a wet mix method (Figure 1.11). The process of selecting the best method, mix designs and field configurations depends on the knowledge of the soil conditions and desired outcomes. To this end, common materials and the mechanisms of addition along with construction and testing methods to verify performance are presented in Chapter 6.

1.3.4 Stabilization and Solidification

The improvement of ground at contaminated land and hazardous waste sites involves additional considerations, materials and methods beyond those that might be used for ground improvement for geotechnical purposes. Much of the equipment and many of the construction methods are the same as, or similar to, those discussed in Chapter 6. For example, Figure 1.12 shows stabilization and solidification of a contaminated site. Like many contaminated sites, multiple methods of site remediation were employed as a system to contain the contaminants and mitigate the risk to public health and the environment. At this site, stabilization and solidification were used for the upper portion of the area of the disposal pits along with a vertical cutoff (Chapter 6) to control and contain the remaining contaminated soil, sludge, and ground water.

The special nature of contaminated ground as well as protection of public health and the environment requires additional reflection. For these applications, topics such as contaminant transport and bonding mechanisms need to be coupled with traditional considerations such as strength, permeability and compressibility. These topics are presented in Chapter 2 and discussed in Chapters 6 and 8.

1.3.5 Grouting

Grouting, as a means of ground improvement, consists of injecting, usually under pressure, a fluidized material (grout) into the subsurface. The grout then either fills pore space or displaces soil, producing stronger soil formation. Grouting techniques include permeation grouting, fracture grouting, compaction grouting, and jet grouting (a form of soil mixing). Mechanistically, each technique is different, using different materials, methods and design methodologies.

Grout materials often "set" or harden after injection. Chemical grouts, such as silicate grouts, can have low viscosities and penetrate small void spaces. Most cement grouts, particularly those made with Ordinary Portland cement, cannot penetrate small voids but work well in rock containing open fractures and voids. Successful grouting programs are developed with an in depth understanding of the rheological properties of the grout (viscosity, set time, and stability) to predict the movement of the grout in the subsurface.

Compensation grouting is of special importance in urban areas. For example, construction of CrossRail in London included the construction of new railway tunnels and stations in an already crowded subsurface environment. Given the above ground environment that includes many historic and aesthetic structures along the route, techniques to avoid damage to existing structures were required. Excavations for tunnels and stations below grade would inevitably cause surface movements if not for the ability to "compensate" for the subsurface movements via grouting. Thus, surface movements are regularly anticipated, monitored and corrected by subsurface compensation grouting. Figure 1.13 schematically illustrates the benefits of compensation grouting to the minimization of settlement of buildings along a tunnel alignment. Analysis of monitoring data to detect movements can lead to the decision to inject grout under pressure at specified locations to compensate for the detected movements. Compensation, and other types of grouting, are discussed in Chapter 7.

1.3.6 Dewatering

There are times that ground is unstable only because groundwater is present or flowing in such a way as to destabilize the soil. While grouting (Chapter 7) and cutoff walls (Chapter 8) are two ground improvement methods that can reduce hydraulic conductivity and improve stability, there are numerous occasions when dewatering may be a better choice. Without proper groundwater control, flowing groundwater can result in bottom heave, unstable slopes and difficult or impossible working conditions. Figure 1.14 shows an excavation below the water table in a stratigraphy of sand overlying a silt of lower permeability. Even with deep dewatering wells, three meters on center, seepage between the wells at the interface between the sand and the silt resulted in localized and progressive slope instability.

Ground improvement by dewatering is a widely used, but often difficult, technique that requires a detailed knowledge of subsurface conditions, theoretical understanding of groundwater flow, and experience. Dewatering is well covered in many texts, including Powers et al. (2007).

1.3.7 Consolidation

While compaction (Chapter 4) is densification at constant water content, consolidation is densification at decreasing water content (Chapter 5). As a result, consolidation is a time-dependent process, as it takes significant time for water to leave clay. During consolidation, soils gain strength and their compressibility is reduced. Soft, compressible, fine-grained soils are prime candidates for ground improvement by consolidation. Soft cohesive soils generally have low hydraulic conductivities and, since the time-rate of consolidation depends upon soil permeability, the time required to consolidate soft cohesive soil may exceed the time available in the construction schedule. In these cases, consolidation can be enhanced by inserting vertical drains, either sand, or prefabricated. Traditionally sand drains were installed to shorten the drainage path and speed up the consolidation process. Prefabricated vertical drains are now more commonly used. Figure 1.15 shows a typical use of vertical drains to speed consolidation of soft ground beneath an embankment. Consolidation, to improve the properties of ground using techniques such as vertical drains, preloading and vacuum consolidation, is discussed in Chapter 5.

1.3.8 Mechanically Stabilized Earth

For thousands of years, masonry structures were built in such a way as to impart compressive stresses on the stone building materials. Arches were commonly used to span openings as this configuration assured the masonry materials were in compression. This building approach was used because stone has little tensile strength but large compressive strength. Similarly, soils have negligible tensile strength but large compressive strength. Soils work well to support structures and serve as earthen structures when in compression. The introduction of tensile reinforcement, first popularized as Reinforced Earth™, in the 1960's, opened the door to a wide range of applications including the now widely used mechanically stabilized earth (MSE) retaining walls. The enormous benefit of reinforcement is illustrated on Figure 1.16. Not only can a vertical face of fill be achieved but a reverse batter as well.

The benefit of reinforcing is further illustrated to students via the ASCE GeoChallenge, a student competition. Shown on the left side of Figure 1.16 is a sheet of construction paper (the retaining wall face) with strips of brown wrapping paper attached (the reinforcement). Shown on the right side of Figure 1.17 is the completed retaining wall 0.5 m high supporting a sandy backfill and a 22 kg surcharge (in the white bucket). This laboratory experiment demonstrates the important improvement in granular soil strength by the addition of even modest tensile reinforcement. Chapter 10 discusses forms and uses of geosynthetic reinforced soil.

1.3.9 In Situ Barriers

In situ vertical barriers (cutoff walls) have been used for over 40 years to control the horizontal flow of ground water in the subsurface. Improving the ground conditions, by reducing the flow in the horizontal direction has been commonly used for dewatering to improve slope stability and reduce water flow into excavations. In the 1980s, these same barriers came into widespread use for environmental applications to control of contaminant transport in the subsurface. Engineers also know and acknowledge that many of the dams and levees constructed over the last 100 or more years need improvement. Issues with seepage and stability jeopardize their performance, particularly during flood events. Thus, in situ barriers (cutoff walls) have found widespread use to improve the properties of the underlying materials and improve the properties of the dam or levee.

The Herbert Hoover Dike in Florida, USA, is a prime example of the use of a barrier wall for levee rehabilitation in response to seepage and piping problems. In order to cut off seepage through and beneath the dam, a cutoff wall was installed (Figure 1.18). The wall, 0.7 m wide and averaging 22 m deep, penetrated the dike and the underlying layers of peat, sand and limestone. As a result, existing piping paths were cut off, the seepage path was lengthened, and exit gradients were reduced.

There are myriad materials that may be used in cutoff walls and numerous ways to construct them. The desired final product is usually a cutoff wall that is homogeneous and has a low permeability (hydraulic conductivity). Often there is a moderate strength requirement as well. Special considerations of compatibility between the barrier and the contaminants are needed when these barriers are used to control contaminant transport around waste or contaminated land sites. Materials, methods, design and analyses of cutoff walls are discussed in detail in Chapter 8.

1.3.10 Future Developments in Ground Improvement

While many ground improvement techniques are tried and proven, there are continuous developments in design, equipment, and construction techniques for these established methods of ground improvement. No doubt there will be new publications reporting on these developments coincident with, and after the completion of this text. This text to aid in understanding, evaluating, and adopting new developments.

In addition to emerging developments and improvements to existing technologies, some pending developments may prove to be entirely new approaches to ground improvement. One excellent example might be termed biogeotechnical ground improvement. There is a rich microbial environment in soils. Microbes participate in biogeochemical reactions, continuously reproducing and dying off. The ways microbes can affect soil behavior include, but are not limited to, mineral precipitation, mineral transformation and biofilm growth. Mineral precipitation can result in stronger, stiffer soils, yielding improved bearing capacity, liquefaction resistance and reduced compressibility. Biofilms can also reduce permeability, forming subsurface barriers.

Figure 1.19 shows an idealized cross-section showing various biogeotechnical ground improvements including stabilization of ground surrounding a tunnel, improved slope stability, low permeability barrier to control subgrade water, and improved erosion control.

In addition to developments like biogeotechnical ground improvement, the future is likely to reveal the development and use of existing materials and methods in ways that they are not currently used. While not in widespread use, mixing plastic fibers to increase the strength of sand (Park and Tan 2005; Gray and Ohashi 1983) and the use of geofoam to reduce earth pressures on retaining walls (Horvath 2010; Dasaka et al. 2012) are gaining use. Benefits of reusing a variety of waste materials, such as recycled gypsum (Ahmed and Issa 2014), and electrokinetics for the stabilization of soft clay (Lamont-Black et al 2012; Malekzadeh and Sivakugan, 2017), are being studied.

It is likely that the future of ground improvement will provide for explicit considerations of sustainability when deciding what, if any, ground improvement method to employ. Historically, geotechnical engineers were primarily concerned with 1) providing an adequate factor of safety against failure of soil, 2) controlling settlements and movements of the ground, and 3) cost. Environmental and sustainability considerations are an important part of the decision process. Considerations of noise, historically or architecturally important structures, archeological finds, and inconvenience to the public are essential considerations when employing ground improvement. At the time of this writing (2020), it is clear that future projects will need to explicitly consider sustainability and legacy effects in the decision process.

1.4. Importance of Construction

There is a common thread that weaves through this chapter and this book: the design and performance of ground improvement is inextricably linked to construction. One cannot "design" a ground improvement program without a full understanding of the construction means and methods. In fact, credit for the development of ground improvement techniques lies largely with innovative contractors. Many of the experts in the field of ground improvement are or were contractors.

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Chapter 12

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