7 REFERENCES

- Matalucci, R. V. and Dennis S. Miyoshi (1997). *An Introduction to the Architectural Surety® Program*, *Proceedings of the Conference on Architectural Surety®: Assuring the Performance of Buildings and Infrastructures*, Sandia National Laboratories, Albuquerque, NM, May 14-15, 1997.

- Matalucci, R. V. and Dennis S. Miyoshi, Sharon L. O'Connor (1998). *An Introduction to Architectural Surety® Education*, SAND98-2086, Sandia National Laboratories, Albuquerque, NM, September 1998.

- Matalucci, R. V. (2000). *Critical Facility Design Needs (Department of Energy): An Architectural Surety® Perspective*, *Protecting People and Buildings from Bomb Damage Conference*, National Academy of Sciences, Washington, DC, November 28-30, 2000.

- Matalucci, R. V. (2002b). "*Risk Assessment Methodology for Dams (RAM-D*SM*)*", Proceedings of the 6th International Conference on Probabilistic Safety Assessment and Management (PSAM6), San Juan, Puerto Rico, Vol. I, pp. 169-176, June 2002.

- Matalucci, R. V., Thomas Baca, and John Strothman (2002a). *Security Risk Assessment Procedures: Countering Terrorism and Other Threats*, American Society of Civil Engineers (ASCE) Continuing Education Units Course. Seminar Locations: Washington, D.C., December 4-6, 2002; Las Vegas, Nevada, February 5-7, 2003; Palm Springs, California, February 11-13, 2004; Phoenix, Arizona, September 28- October 1, 2004; Seattle, Washington, October 20-22, 2004; Arlington, Virginia (FAA on-site), October 26-28, 2004.

- Biringer, B., Matalucci, R.V., and O'Connor, S., (2007). *Security Risk Assessment and Management: A Professional Practice Guide for Security of Buildings and Infrastructures*, John Wiley and Sons, Hoboken, New Jersey, 2007.

The Role of Foundation Design in Progressive Collapse of Buildings

N. O. Nawari, Ph.D., P.E., M.ASCE[1]

[1]College of Architecture and Environmental Design, 304 Taylor Hall, Kent State University, Kent, Ohio 44242, nnawari@kent.edu

ABSTRACT: While statistical data indicate that risk of progressive collapse in buildings is very low, loss of human life and severe injuries would be significant when a fully occupied multi-story building encounters partial or total failure. As a result of recent terrorist attacks on buildings throughout the world, particularly U.S. owned and occupied buildings, and recent natural hazards like Katrina Hurricane; several U.S. government agencies with large construction programs have developed their own design requirements (GSA 2003; DOD 2005) to provide resistance against progressive collapse. Each agency, however, with its own mission, has adopted different performance objectives for buildings subjected to abnormal loads. Foundation and geotechnical design considerations to provide resistance against progressive collapse are important components of the overall building performance under abnormal loadings. This work discusses the role of geotecnical and foundation system design considerations to reduce the likelihood of progressive collapse of buildings in the event of anomalous loadings. This includes outlining of acceptable risk approach to progressive collapse along with definitions of threads, events control, risk mitigation and practical recommendations for enhancing foundations resistance to progressive collapse.

INTRODUCTION

The 1995 attack on the Oklahoma City Murrah Building was a major thrust to raise government interest in explosion protection for its facilities in the United States and oversees. In response, the federal Interagency Security Committee (ISC) addressed the issue promptly by developing a blast-resistance standard outlining new criteria for design. Subsequently, the horrific structural collapses of Sept. 11, 2001 and the catastrophic damages caused by hurricane Katrina 2005, refocused attention and emphasis on design for extraordinary loads.

In light of these events, two major building owners, the General Service Administration (GSA) and the Department of Defence (DoD) are requiring engineers to consider building security as additional criterion. Even private sector owners and developers of high profile buildings are taking a serious look at security risks as their buildings may be considered as target of both domestic and international terrorists.

The primary design objective is to save the lives of those who visit or work in these government buildings in the unlikely event that an explosive terrorist attack occurs. In terms of building design, the first goal is to prevent progressive collapse which historically has caused the most fatalities in terrorist incident targeting buildings. Beyond this, the goal is to provide design solutions which will limit injuries to those inside the building due to impact of flying debris and air-blast during an incident. In some cases, secondary objectives may need to be considered such as maintaining critical functions and minimizing business interruption.

Progressive collapse is defined as a situation where local failure of a primary structural element(s) progresses to adjoining members, which in turn leads to additional collapse. Hence, the extent of total damage is disproportionate to the original cause. Different standards describe the term in slightly various ways. ASCE 7-05 defines the term as:" the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or disproportionately large part of it." On the other hand DOD gives the following definition: "A progressive collapse is a chain reaction of failure of building members to an extent disproportionate to the original localized damage. Such damage may result in upper floors of a building collapsing onto lower floors." The GSA 2003 defines the expression as "Progressive collapse is a situation where local failure of a primary structural component leads to the collapse of adjoining members which, in turn, leads to additional collapse. Hence the total damage is disproportionate to the original cause."

Regardless of the definition, blast loading or other abnormal events can cause progressive collapse due to damage of some key element(s) which can either make the structure unstable or trigger the failure of the main portions of the structural system. Explosion generally results in a high-amplitude impulse loading which lasts for a very short period of time and produces high pressure loading. The loading in many situations is local in the sense that only those elements closest to the blast may be directly impacted. Elements far from the blast site may experience little or no direct impact due to sharp dissipation of blast energy with distance. The forces experienced by structural components depend on the size, geometry and proximity of the explosion. Because all of these parameters can vary, it is not easy to accurately predict the force level that a particular structure could experience as a result of an unexpected blast.

Risks of these events cannot be totally eliminated; rather it must be controlled. Building codes are key tools for engineers to manage risk in the interest of public safety. The provisions for foundation and structural design in codes and standard for load combination and safety and partial safety factors addresses risks in building performance. However, risks of blast events have not been part of limit states in previous codes and quite often managed judgmentally. However, the aftermath of recent natural and terrorists disasters has made it clear that judgmental approaches to risk management are not sufficient. Rational approaches to progressive collapse mitigation require risk-informed analysis and assessments.

THREAD DEFINITION

Federal guidelines define three threat levels that delineate blast protection of building structures:

• A high threat level entails a verified high threat of attack. These projects typically are buildings of high importance, buildings whose loss will have high consequences or those that are cultural icons.

• A medium threat level consists of a verified threat of attack. These buildings may be regional symbols, or their loss will highly impact governing powers.

• A low threat level constitutes a suspected threat. These buildings may be regional symbols, or their loss will have moderate consequences.

To gain a systematic approach of investigating terrorists threads, FEMA 427 classifies terrorist threats into the following groups:

Explosive Threats:

- Vehicle weapon
- Hand-delivered weapon

Airborne Chemical, Biological, and Radiological Threats:

- Large-scale, external, air-borne release
- External release targeting building
- Internal release

Although the dominant threat mode may change in the future, bombings have historically been a favorite tactic of terrorists. Ingredients for homemade bombs are easily obtained on the open market, as are the techniques for making bombs. Bombings are easy and quick to execute. Finally, the dramatic component of explosions in terms of the sheer destruction they cause creates a media sensation that is highly effective in transmitting the terrorist's message to the public, as was shown in the UK's car bombs in London and Glasgow June 2007.

The primary threat is mostly a vehicle weapon located along a secured perimeter line surrounding the building (see Figure 1). Depending on the accessibility of the site to vehicles there may be more than one line of defense to consider. The outermost perimeter line is often a public street secured against vehicular intrusion using barriers and with limited secured access points. The size of the vehicle weapon considered outside the perimeter line may vary from hundreds to thousands of pounds of TNT equivalent depending on the criteria used. Weapon sizes vary depending on the specific criteria used and may be obtained from the federal agency client on a need to know basis.

This threat is to be considered on all sides of the building with a public street or adjacent property lines along the secured perimeter line. Because air-blast loads decay rapidly with distance, the highest loads are at the base of the building and decay with height. Benefit of these reduced loads is usually not realized in terms of reduced design requirements except for high rise structures.

Because explosive attacks are expected to remain the dominant terrorist threat in the near future, this work focuses primarily on bomb (explosion) threats, likely targets, and likelihood of occurrence.

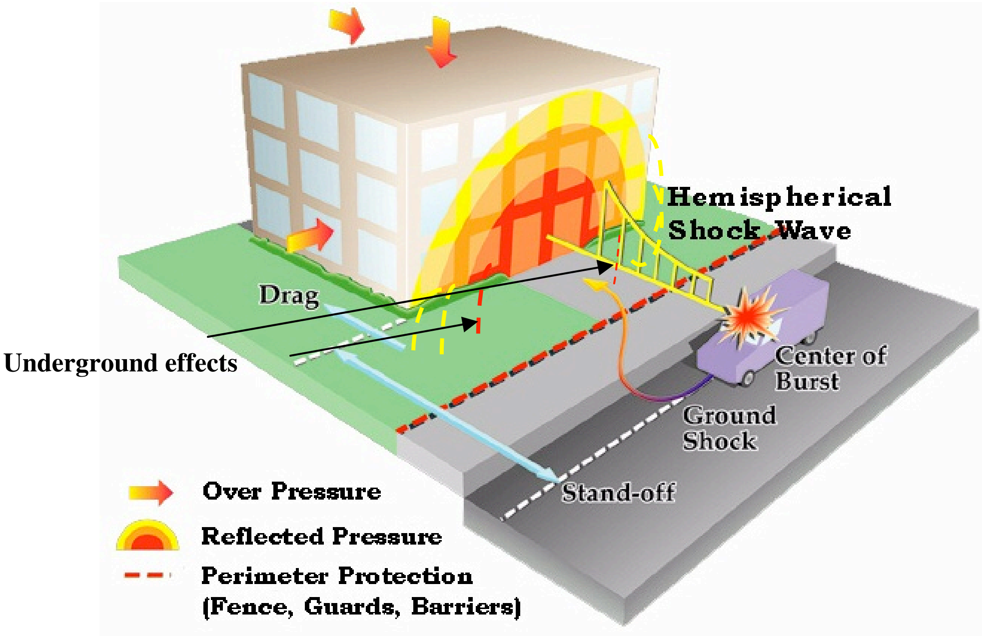

Figure 1. Vehicle Weapon Threads (FEMA 427)

DAMAGE MECHANISMS

Building damages due to a blast event can be categorized into the following groups (see Figure 2):

- Non structural damages; generally taking place on the building envelope.
- Superstructures damages: beams, columns, slabs, … etc
- Substructures damages: footings, raft, pile, and soil failures.
-

It is notwithstanding that these hazards are interrelated during an explosion event and the occurrence of one may lead to the other with the likelihood of a progressive collapse. Figure 2 below illustrates the relationships among these groups.

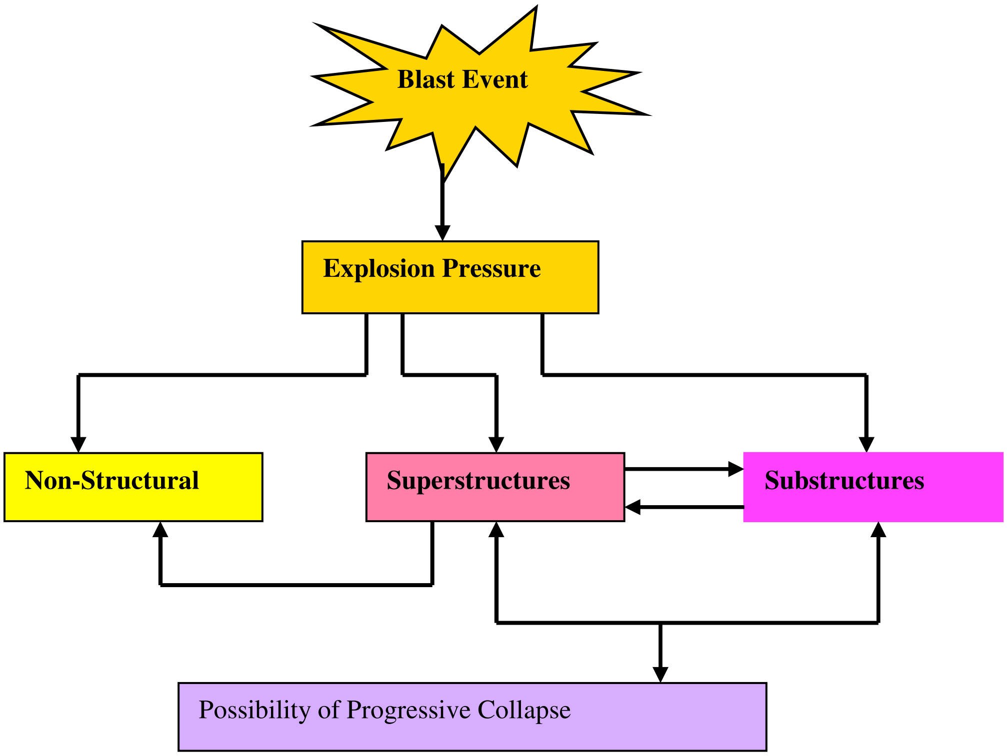

Figure 2. Building's hazards due to Blast Event.

Superstructures

The response of a structure to blast loading is different from its response to typical static and dynamic loads because of the very short duration and extreme pressure loading caused by explosion. According to FEMA 427, the structural damages caused by large exterior explosion can be summarized as follows:

- The pressure wave acts on the exterior of the building and may cause window breakage and wall or column failures;
- As the pressure wave continues to expand into the building, upward pressures are applied to the ceilings and downward pressures are applied to the floors;
- Floor failure is common due to the large surface area upon which the pressure acts; and
- Failure of floor slabs eliminates lateral support to vertical load-bearing elements, making the structure prone to progressive collapse

All of the damages mechanisms described by FEMA(2003), DOD(2005) or GSA(2003) are primarily focused on superstructure effects (Figure 3). Foundations and geotechnical aspects were not considered in these reports. The next section examines different foundation and geotechnical damage scenarios caused by blast effects.

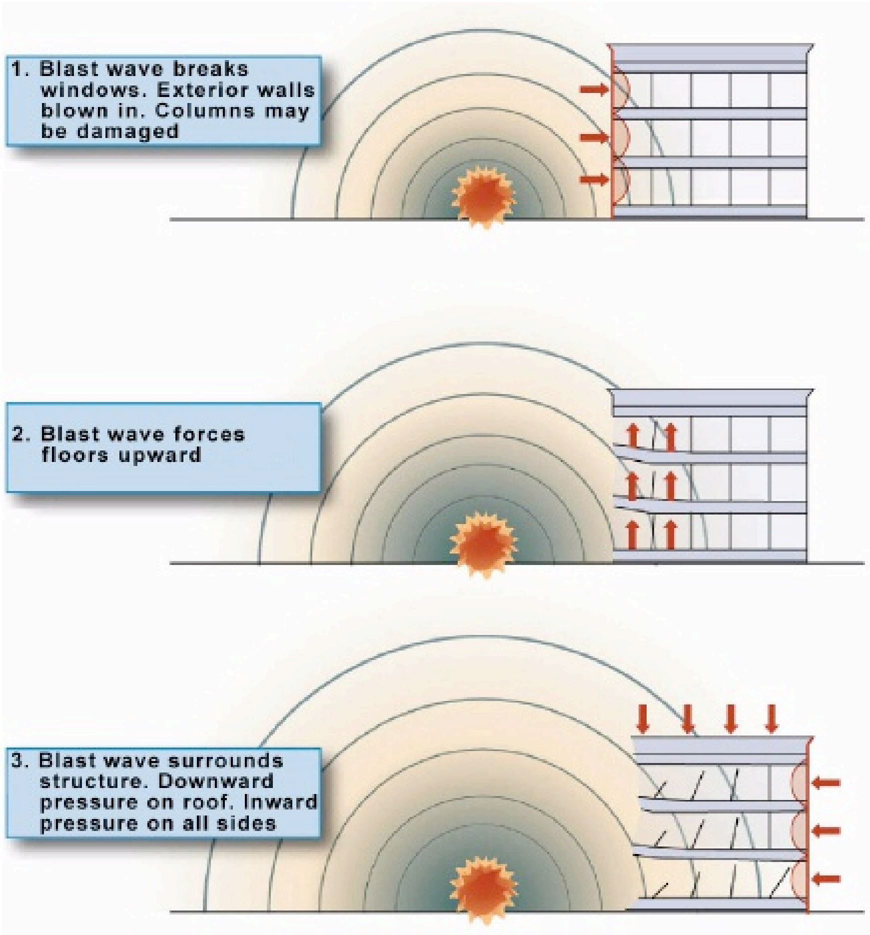

Figure 3. Sequence of Building Damage due to Vehicle Weapon. (FEMA 427)

Substructures

Because there are many potential means by which a local collapse in a specific structure may propagate from its initial extent to its final state, there is no universal approach for evaluating the potential for progressive collapse in buildings. This case specific behavior differentiates progressive collapse from other well defined structural engineering concerns, such as design to resist gravity, wind, seismic or vibration loads. The following general statement can be made, however, of all progressive collapse scenarios: When an initiating event causes a local failure, the resulting failure front will propagate through the building structure until specific structural conditions in its path arrest the progression of failure, or until the remaining structure becomes statically unstable and the entire building collapses. Because progressive collapse is a dynamic event, the failure boundary divides the structure into a zone that has not yet experienced the effects of the progression of failure and the failed portion of the structure. A failure front may propagate laterally, vertically, or both. Blast affects foundations either directly or indirectly or both. In the first case explosion reaches part of the foundations and causes damages on the footings or piles foundations (see Figure 4). In addition to these damages, excessive dynamic forces impose additional stresses in other existing foundation structures.

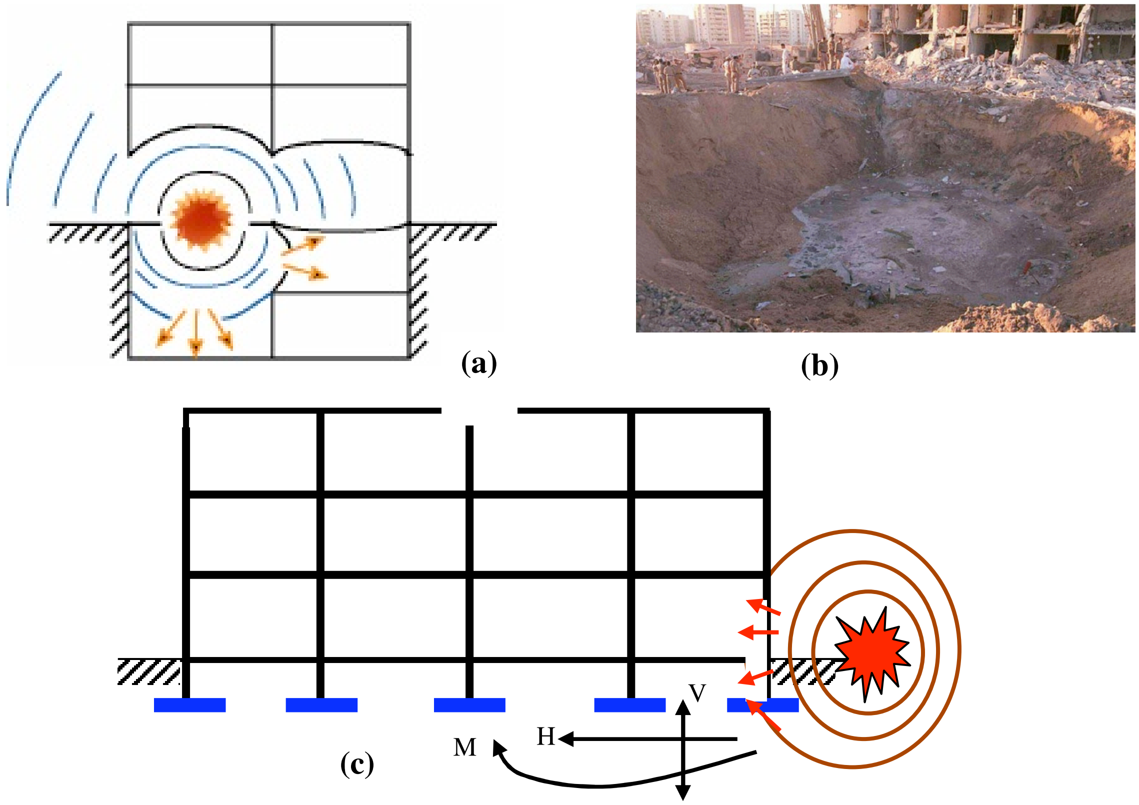

Figure 4. Explosion Affecting directly both Super- and sub-structures.

In figure 4 above, detonation of explosion inside (figure 4a and 4b) or outside (Figure 4c) the building caused damages to the framed superstructure and at the same time foundation was directly affected by the explosion. Furthermore, additional vertical, lateral and vibration forces in the foundation domain due to the blast are generated. As a result, these forces may cause additional drift of the structural frame. The magnitude of the drift and the associated stability issues depends upon the type of the frame (rigid or flexible), type of foundation (single, combined footings, or piles) and the geotechnical properties of the foundation soils (Figure 5) along with the strength of blast.

The second scenario is when explosion damages only parts of the superstructure. Figure 3 illustrates some possible collapses of the superstructure. The failure of columns, beams and slabs will generally be associated of load redistribution and collapse may progress if the remaining elements are at the stage of reaching their ultimate limit states. As a consequence, foundation structures (single footing, combined footings, raft, or pile foundations) will be experience to additional loading conditions. For instance, figure 7 shows the redistribution of forces after the loss of an exterior column. In the next sections, damage mechanisms are discussed for single and combined footings. Next article will investigate damage scenarios for raft and pile foundations.

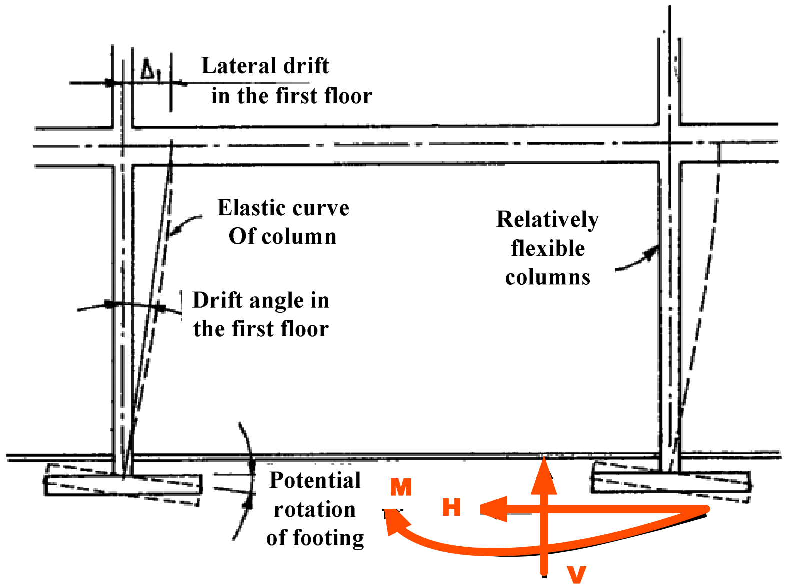

Figure 5. Drift due to blast

Single Footing Foundations

In the case of loss of any external or internal column due to blast, loads on the other adjacent remaining footings will increase due to the load redistribution and changes in tributary areas (see figure 6). Thus, changes in the applied compression (P), shear force (H) and bending moment (M) may exceed the design values causing structural failure of the footing.

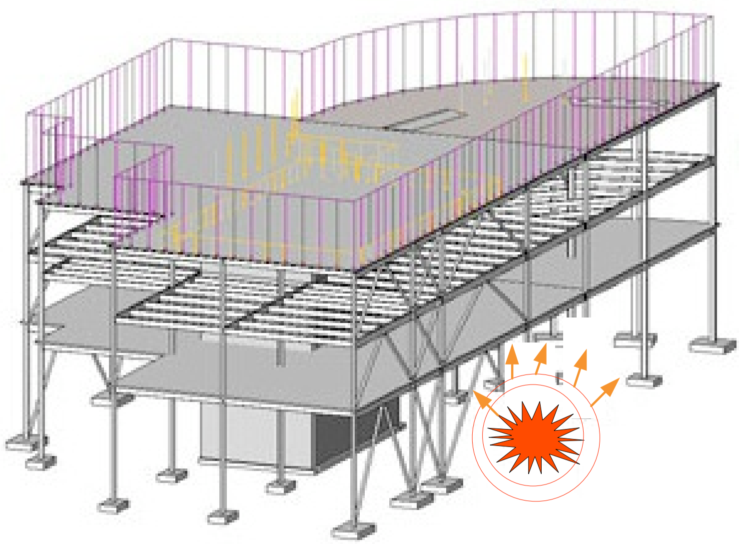

Figure 6. Removal of exterior Columns by detonation of explosives.

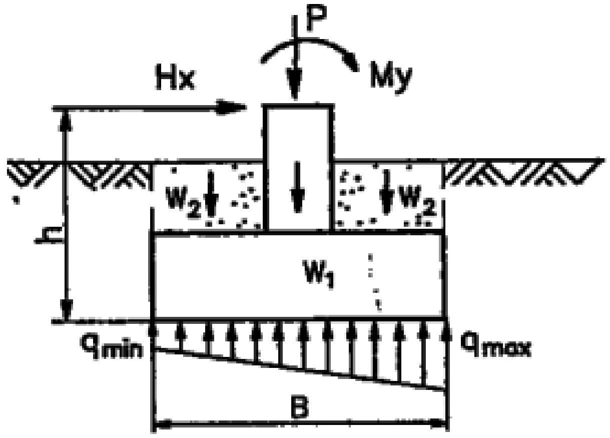

Figure7. Forces acting on a pad foundation.

Other risk of this abnormal loading is excessive settlement or bearing capacity failure. For example, in figure 7 if the value of the soil pressure q_{max} after the load redistribution surpasses the safe contact bearing pressure soil bearing failure takes place and the support provided by the spread footing is practically lost. Soil liquefaction and collapses may also be experienced by the supporting subsurface soils.

Combined Footing

Removal of a column supported by a combined footing due to blast event would cause redistribution of forces on the remaining adjacent columns in the combined footing which in turn affect the contact pressure distribution. Figure 8a illustrates a combined footing designed such that a uniform soil pressure would result in the contact area.

Under an abnormal load case of a blast, the soil pressure distribution after the removal of one or more columns is entirely different than the uniform pressure assumed during the design phase.

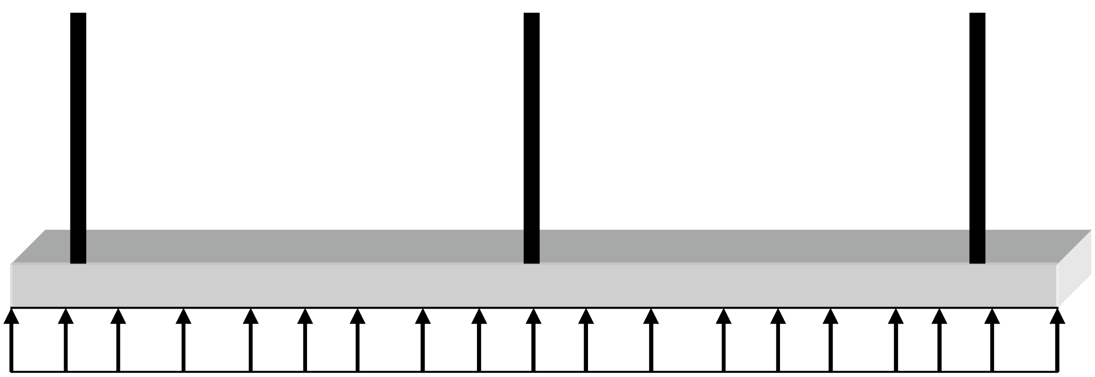

Figure 8a. Soil pressure distribution under a combined footing.