Seismic Vulnerability of Lifelines in Greater Cairo

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ABSTRACT:
The prediction of potential damage to the built environment from future earthquake events is essential for mitigating against seismic risk, and is necessary for estimating the potential economic losses resulting from such events. This paper outlines a methodology for estimating damage to Greater Cairo's built environment, with emphasis on the natural gas and electricity networks. The vulnerability of the natural gas and electricity networks is assessed through the use of cut sets, fragility curves and the evaluation of the capacity of the supply networks. Moreover, both networks are linked, and so the proposed method accounts in a realistic way for the nature of the built environment where damage to one aspect can lead to further damage or losses in another. Furthermore, the macro-economic consequence of such damage, accounting for possible direct and indirect losses, is evaluated. This provides an overall loss framework that links the damage module to the economic module, with the model being potentially expandable to include further aspects of the built environment.

Keywords: Loss Estimation, Lifeline Vulnerability, Egypt

1. INTRODUCTION

Egypt is the 12th largest African country, with an area of just over 1 million km^2, and a population of nearly 82 million, which is expected to rise to 113 million by 2036 (Khalifa et al., 2006). Even though this represents a relatively small population density of 80 people/km^2, most of this population is concentrated along the Nile Valley and so the actual population density is high. Moreover, due to this high population density and the nature of the built environment that is lacking in seismic provisions, Egypt appears to be vulnerable to the occurrence of a seismic event. This was evident during the October 1992 Ms=5.4 Dashour earthquake, originating 26 km southwest of Cairo, which would have caused minimal damage in economically developed countries, but caused damage estimated to be one billion U.S. Dollars in Egypt (Badawai and Mourad, 1994). The Dashour earthquake also highlighted the centralised nature of the Egyptian economy, where economic losses in Greater Cairo highly resonate through the national economy.

Greater Cairo is a conglomeration of two of Egypt's 27 governorates; Cairo and Giza. Due to the close proximity of these two governorates their boundaries are only of political and administrative use, and therefore these governorates are usually grouped together to form Greater Cairo. This region hosts nearly 20 percent of the Egyptian population (CAPMAS, 2006), further highlighting the economic significance of Greater Cairo and the importance of analysing the vulnerability of its built environment.

Lifelines play an integral role in driving a nation's economy forward. Moreover, with an increasing population, the lifeline systems need to be expanded to meet the increase in demand, and to allow the continuation of the current economic development. Various infrastructure projects are being carried out throughout Egypt with the purpose of catering for the rise in population and the increase in trade. In 2008 the Egyptian government announced the investment of 16.3 billion U.S. Dollars into transportation and water networks (ADB, 2009), while the enhancement and construction of 17 power plants are also underway (MOEE, 2009; ADB, 2007).

While a robust infrastructure helps maintain economic growth, a vulnerable infrastructure can lead to major economic losses in the case that the operation of this infrastructure is interrupted. This was apparent during the Northridge 1994 earthquake, where damage to the communication and transportation systems resulted in large economic losses (Torres-Vera and Canas, 2003). In assessing the vulnerability of lifelines, most previous studies have analysed a single lifeline at a time (Rose et al., 1997; Shinozuka et al., 2007; Song and Ok, 2009). This method, while simplifying the analysis, overlooks the dependency between each of the lifeline systems. Since each of the lifeline networks is dependent on the other, damage to one affects each of the other networks. Therefore, it is essential that the vulnerability of multiple lifelines be analysed, and the dependency between each of these networks be modelled to reflect the physical damage and economic losses resulting from an earthquake occurrence in a more realistic manner.

The natural gas network represents one of Egypt's most important lifeline systems. According to the Egyptian Ministry of Finance (MOF) this network represents 50 percent of Egypt's energy consumption and 8 percent of its GDP (MOF, 2010), clearly illustrating the economic importance of the network. Thus, the vulnerability of the natural gas network is analysed in this study. Furthermore, since a number of electricity stations are fuelled by natural gas, analysing the electricity network provides an opportunity for modelling the dependency between two lifeline networks. Moreover, with several electricity blackouts having occurred in Greater Cairo since 2010, it appears that the electricity network is vulnerable and already struggling to meet current demand. This illustrates that with the occurrence of a seismic event the electricity network might be severely disrupted, causing economic losses, and delaying the recovery process. Damage to either of these networks could cripple the economy, not only because of the replacement cost of the damaged network components, but also because of the business interruption which can result from such damage. For example, the interruptions caused by the 1994 Northridge earthquake resulted in 6.4 billion U.S. Dollars in business losses.

This paper presents a methodology for assessing the vulnerability of both the natural gas and electricity networks, while modelling the dependency between each of these networks. Moreover, the direct and indirect losses resulting from damage to these networks are evaluated and briefly outlined.

2. NATURAL GAS

2.1 Overview

Natural gas compromises one of Egypt's most important resources, with a reserve of 58.5 trillion cubic feet (CF) (EIA, 2010). According to the Ministry of Petroleum (MOP), 2.135 trillion CF of this reserve was produced in 2007, of which 1.52 trillion CF was used to meet local demand, and 0.615 trillion CF were exported (MOP, 2010). This demonstrates that natural gas is not only exported, but is also required to maintain social welfare and drive the economy forward. The dependence on natural gas has increased exponentially over the years. Between 1980 and 1984, only 90,000 households had natural gas connected to them, but just prior to the turn of the millennium this figure had risen to 930,000, and has further increased to 3.5 million of the following ten years (MOP, 2010). According to the *Egyptian Natural Gas Holding Company (EGAS*), 47 percent of national consumption occurs in Greater Cairo (EGAS, 2010). Due to the centralised nature of the Egyptian economy, and its reliance on Greater Cairo, it is evident that disruption to the natural gas network might lead to severe economic losses.

2.2. Greater Cairo Natural Gas Network and Components

Four main physical system components exist in the Greater Cairo natural gas network whose seismic performance needs to be assessed: compressor stations, pressure reduction stations, regulator stations, and pipelines. Natural gas is pressurised through the network, and therefore compressor stations are needed to maintain adequate pressure through the system. Moreover, as natural gas is transported to the customer the pressure is reduced periodically, and therefore pressure reduction stations (PRS) are required throughout the network. Additionally, since pressure can fluctuate above or below the required levels throughout the network, regulator stations are used to ensure that the pressure is at the level needed. These regulator stations are placed downstream of the PRS.

The last of the components are the pipelines used to transport the natural gas. These pipelines vary in diameter depending on the pressure of natural gas being transported by the pipeline. Four main pressure lines exist within the natural gas network; 70, 30, 7 and 4 bars. The 70 and 30 bar lines are mainly transmission lines and use 16 and 24 inch diameter pipelines. The 7 and 4 bar lines use 4, 6, 8, 10 and 12 inch diameter pipelines. The Greater Cairo natural gas network is shown in Figure 1.

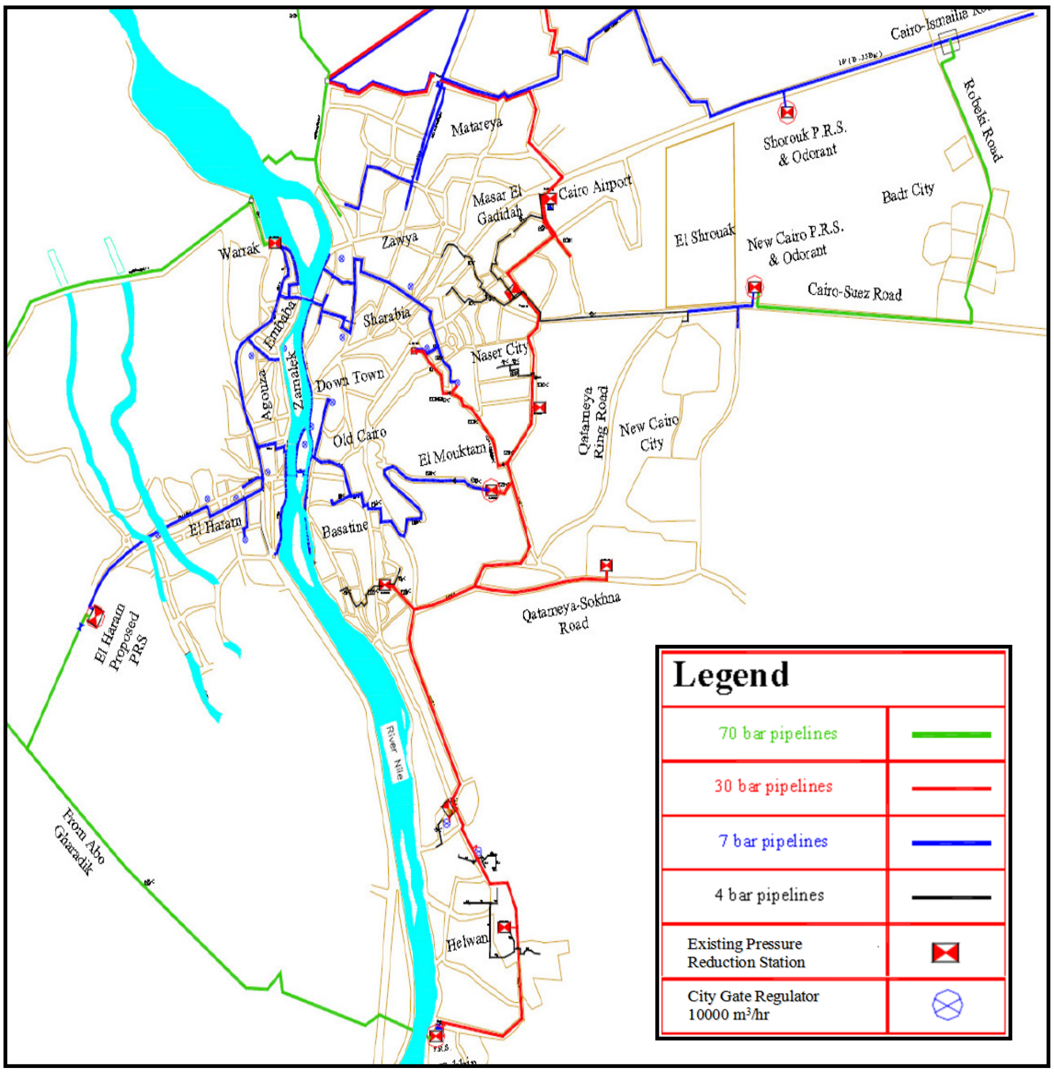

Figure 1 Greater Cairo's natural gas network, modified from EGAS (2007)

In order to assess the vulnerability of these components, the natural gas network presented in Figure 1 was overlaid upon a GIS map of Greater Cairo districts. This enabled the determination of the coordinates of pipelines and stations, and the determination of which district each component was in. This geographic link is essential for estimating economic losses. Each station was given a unique numerical ID, whereas each pipeline was identified by two IDs, one for its start point, and one for its end point.

2.3. Component Damage

Assessing the damage to natural gas stations is straightforward. The process involves calculating the peak ground acceleration (PGA) at the station location, and then, based on this and existing fragility curves, the probability of damage for the station can be estimated. Song and Ok (2009) propose that the fragility curves for compressor stations be used for PRS, since they possess many of the same physical components. Accordingly, the fragility curve shown in Figure 2 is used.

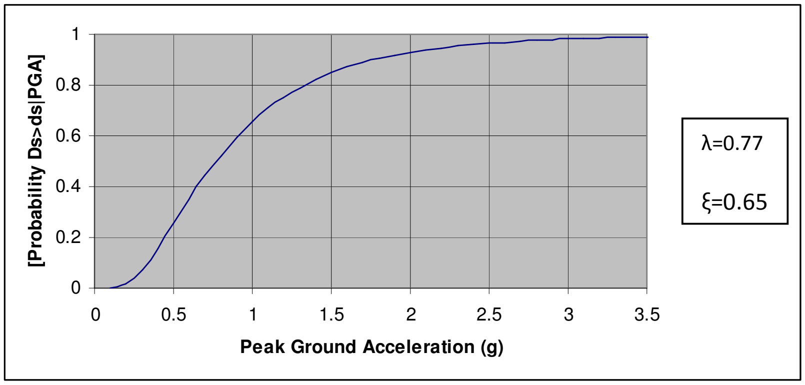

Figure 2 Fragility curve for PRS and regulator stations, λ and ξ are the mean and standard deviation of the lognormal distribution respectively (Song and Ok, 2009)

Estimating pipeline damage, on the other hand, is far more complex. Since pipelines can span over several districts, where the spectral accelerations at each of these locations differ, the pipe segment needs to be discretized into smaller segments as proposed by Song and Ok (2009) and the peak ground velocity (PGV) at the centre of each of these smaller segments is then estimated by taking into account the spatial correlations in ground-motions fields. Knowing the start coordinate and the end coordinate of the entire pipe segment, from the component IDs, the pipe segment can be discretized, and the midpoints of each of these segments can be determined. PGV is used in estimating damage to the pipe segments rather than PGA because peak horizontal strain in the soil due to seismic waves is proportional to PGV (Newmark and Rosenblueth, 1971; St. John and Zahrah, 1987). Knowing the PGV at the midpoint of the pipe segment, the probability of damage of the segment can be estimated as follows (FEMA, 2003):

$$P = 1 - \exp(-\nu \cdot \Delta l) \tag{2.1}$$

$$\nu = 0.3k \cdot PGV^{\gamma} \tag{2.2}$$

where, Δl is the length of the segment being analysed, which is typically 1 km, and k and γ are model parameters. ν is a measure of the repair rate of the pipe segment, and the values of k and γ are considered as 0.0001 and 2.25 respectively. The entire pipe segment can be viewed as smaller pipe segments linked in series, where the failure of one of these smaller segments will lead to the failure of the entire segment. Accordingly, the probability of damage of the entire segment can be calculated.

2.4. Network Reliability and Supply to districts

Even though the method for estimating the probability of damage of each of the components has been presented, this does not provide the probability that the network fails to supply gas to each of Greater Cairo's districts. Lifeline networks are designed with a level of redundancy that ensures that even if a component is damaged the district being affected can still receive its supply of natural gas from another station. In order to analyse the performance of the network a reliability analysis is used which identifies cut sets and path sets. Cut sets identify the set of components whose failure will lead to a node failing (where a node supplies gas to a given district). A path set identifies the components which, if operating, result in the node being in a state of operation. Moreover, minimum cut sets are sets that do not contain any subsets that are cut sets. For each station, the minimum cut sets are identified. From knowing the probability of failure of each component in the minimum cut set, the probability of occurrence of each minimum cut set $P_{f_{set}}$ can be estimated as follows:

$$P_{f_{set}} = \prod_{i=1}^{n} p_{f_i} \tag{2.3}$$

where p_{f_i} is the probability of failure of each component in the minimum cut set. Since multiple minimum cut sets exist for the same node, the total probability of failure $P_{f_{node}}$ of a given node can be calculated as follows:

$$P_{f_{node}} = \sum_{set=1}^{n} P_{f_{set}} \tag{2.4}$$

Knowing the probability of failure of each station based on Equation (2.4), the probability of supplying a given district can also be estimated. Since a district is supplied by multiple stations, the supply of gas to a given district Gas_p can be determined based on the probability of failure of a given node $P_{f_{node}}$, and the fraction of the total supply to the district coming from that node, S_{node}, such that:

$$Gas_p = \sum_{node=1}^{n} S_{node} P_{f_{node}} \tag{2.5}$$

3. ELECTRICITY NETWORK

3.1. Overview

Electricity is essential in modern society, and is critical for domestic, commercial and industrial activities and processes. Due to the ever-increasing demand for electricity, which is expected to rise at an annual rate of 5.03 percent between 2009 and 2022 (MOEE, 2009), the Egyptian Ministry of Electricity and Energy (MOEE) has restructured its divisions over recent years, with nine regional distribution companies being created to meet the electricity demands throughout the country. Nonetheless, even though the restructuring of the distribution division has aided in the management of the distribution process, electricity generation remains a problem. Since there are limited financial resources available to the MOEE, it has opted to enter into joint venture agreements with multinational companies to design and build various electricity stations. This model helps shift the capital costs and risk of these projects from the MOEE to other entities (CARANA, 2002).

The industrial and residential sectors dominate electricity consumption in Egypt, constituting over 78 percent of electricity usage (MOEE, 2009). This illustrates that damage to the electricity network, especially in a highly populated region such as Greater Cairo, can have severe economic implications.

3.2. Greater Cairo Electricity Network and Components

The Greater Cairo electricity network consists of six main generating stations, with generation capacity ranging from 46 to 1295 MW. These stations are fuelled by natural gas, light fuel, heavy fuel, or a combination of more than one of the fuel types. These fuels then power turbines that are either run by steam, gas, or combined cycle turbines. Most of the stations in Greater Cairo use steam or combined cycle turbines (MOEE, 2009).

The generated power is then transmitted through high-voltage transmission lines that are typically

500KV and 220 KV lines made of copper and aluminium conductors. The voltage is then reduced the closer it gets to the end user through the use of 29 transforming substations throughout Greater Cairo. These substations consist of circuit breakers, disconnect switches, buses, lightening arresters, wave trap, buses, current transformer, potential transformers, coupling voltage transformers and circuit switches. For the purpose of analysing seismic performance and reliability, disconnect switches and buses constitute the critical components (Shinozuka et al., 2007). Greater Cairo's electricity network is overlaid onto a GIS map of Greater Cairo in order to determine the coordinates of each station.

3.3. Network Reliability

Knowing the configuration of each substation, the failure of each line connected to the substation can be estimated through the use of minimum cut sets. For stations connected to one or two stations 1032 minimum cut sets are identified, and 1140 minimum cut sets are identified for stations connected to more than two other stations.

Since the coordinates of each station are known, the probability of failure of network components at each station can be estimated through the use of fragility curves. Fragility curves for circuit breakers, disconnect switches and transformers (Figure 3) were developed by Shinozuka et al. (2007) based on the data collected and the fragility curves developed by the Pacific Earthquake Engineering Research Centre (PEER) (Anagnos, 2001).

After having identified all minimum cut sets, knowing the components that constitute each minimum cut set, and the probability of failure of each component through the use of fragility curves, the probability of failure of each line can be estimated as follows:

$$P_{F_{Line}} = \sum_{cutset=1}^{n} P_{F_{B,DS,CB}} No_{B,DS,CB_{cutset}} \tag{3.1}$$

where $P_{F_{B,DS,CB}}$ is the probability of failure of buses, disconnect switches and circuit breakers and $No_{B,DS,CB_{cutset}}$ is the number of each component in a given minimum cut set. Since a line connecting two substations can fail at either substation then the failure of the line is calculated as:

$$P_{F_{Line}} = 1-\left(1-P_{F_{Line1}}\right)\left(1-P_{F_{Line2}}\right) \tag{3.2}$$

where $P_{F_{Line1}}$ is the probability of failure of the line at the first substation, and $P_{F_{Line2}}$ is the probability of failure of the line at the second substation.

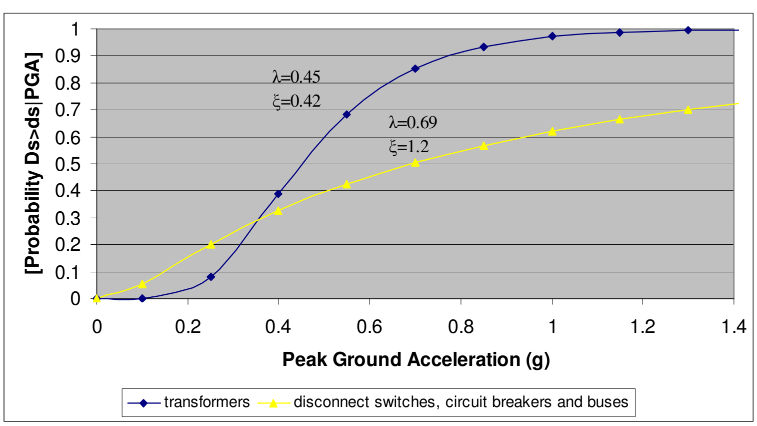

Figure 3 Fragility curves for transformers, disconnect switches, circuit breakers and buses

Even though the probability of failure of each line can be estimated, the behaviour of the network and failure of each station still cannot be. This differs from the natural gas network because even though a line might fail, the substation can still remain operational. The reason for this is that node connectivity is not the only criteria that is used to determine node failure, thus identifying minimum cut sets throughout the network becomes unfeasible. According to Shinozuka et al. (2007), in addition to a substation or line being connected from the source to the point of supply, the voltage being transported by each line cannot be 10 percent greater or less than the original voltage across the line. Moreover, the supply to each substation cannot be greater than 110 percent or less than 105 percent of the demand. If any of these criteria are not met, the line or station is considered out of service.

In order to identify the behaviour of the network including the criteria discussed, the network needs to be treated as a power flow problem, and models capable of solving such problems are used. Matpower (Zimmerman et al., 2011) is one tool capable of doing so, and is used in this study to simulate the behaviour of the network. Initially the intact network is input, after which scenarios of failed lines are run through the model and the behaviour of the network is studied. Since 48 lines exist in the network, and two possible states exist for each line; in service or out of service, 2^{48}=2.815 E14 scenarios exist. Running each of these scenarios is computationally impractical and thus a subset of 100 of these scenarios is randomly sampled. In order to minimise the expected uncertainty associated with sampling a small subset, the process is repeated 10 times. Knowing the probability of failure of each line $P_{F_{Line}}$ the probability of each scenario occurring, $P_{Scenario}$ can be estimated as follows:

$$P_{Scenario} = \prod_{Line=1}^{48} P_{Line} \tag{3.3}$$

When each scenario is run through Matpower, the supply of power to each substation changes, and thus the probability of supply of power to each station $P_{Station_{initial}}$ can be estimated based on the ratio between power supplied to the station when the network is damaged $Supply_{station_{damaged}}$ and when the network is intact $Supply_{station_{intact}}$ as seen in Equation (3.4).

$$P_{Station_{initial}} = \sum_{Scenario=1}^{100} P_{Scenario} \times \frac{Supply_{station_{damaged}}}{Supply_{station_{intact}}} \tag{3.4}$$

3.4. Link to the Natural Gas Network

Since a number of the electricity stations are powered by natural gas, failure of the natural gas network could result in further damage, or at least interruption, to the electricity network. Six electricity stations are run by natural gas, and the ability of these stations to supply the districts they serve is a function of the probability of the failure of each electricity station $P_{Station_{initial}}$ and the probability of failure of the natural gas stations Gas_p that supply them. If failure of any of these stations occurs, the station is incapable of supplying electricity. Thus, the percentage of supply of electricity to the districts $P_{Station_{Final}}$ can be estimated as follows:

$$P_{Station_{Final}} = 1 - \left(1 - P_{Station_{initial}}\right) \times \left(1 - \prod_{i=1}^{n} Gas_{p_i}\right) \tag{3.5}$$

where n is the number of gas stations connected to the electricity generating station.

3.5. Supply to Districts

In order to increase the reliability of the network a level of redundancy is included which ensures that even if a station fails the district that the station serves can still be supplied by another station, which reduces possible economic losses. For a given district to be unable to receive any electricity, all the possible stations that can supply the district have to fail. Accordingly, the percentage of electricity supply $Electricity_p$ can be estimated as follows:

$$Electricity_p = 1 - \prod_{Station=1}^{n} \left(1 - P_{Station_{Final}}\right) \tag{3.6}$$

where n is the number of stations supplying the district. The most important feature of producing the output in the manner shown in Equation (3.6) is that it is consistent with the natural gas network output shown in Equation (2.5). This is essential for developing an economic loss model.

4. DIRECT AND INDIRECT LOSSES

4.1. Overview

The economic impact of natural disasters had been overlooked until the 1990s when several natural disasters which include Hurricane Andrew in 1992, the Northridge earthquake in 1994 and the Kobe earthquake in 1995, occurred (Okuyama, 2007). These events caused severe damage to the built environment, but also caused the economies in the affected regions to come to a near standstill, leading to further losses.

Economic losses can be divided into two categories: direct and indirect losses. Direct losses are relatively simple to model and they relate to the repair or replacement costs of damaged structures, and building and lifeline components (Brookshire et al., 1997). Indirect losses are more complex to calculate, and relate to the business inventory losses, business disruption, reduction in economic output, and the ripple effect throughout the entire economy that results in bottlenecks and a reduction in demand (Brookshire et al., 1997; Boisvert, 1992; Burrus et al., 1992).

4.2. Direct Losses

Estimating direct losses involves estimating the repair and replacement cost of damaged components. Since fragility curves have been used to estimate the damage probabilities *DP* of components in both the natural gas and electricity networks, direct losses for the natural gas DL_G and the electricity DL_E networks are estimated as a function of *DP* and replacement cost as follows:

$$DL_G = \sum_{pipe=1}^{n} DP_{pipe} \times RC_{pipe} + \sum_{station=1}^{n} DP_{station} \times RC_{station} \tag{4.1}$$

$$\begin{aligned} DL_E = & \sum_{DS,CB,Buses=1}^{n} DP_{DS,CB,Buses} \times RC_{DS,CB,Buses} + \\ & \sum_{Transformer=1}^{n} DP_{Transformer} \times RC_{Transformer} \end{aligned} \tag{4.2}$$

where RC_{pipe} is the replacement cost of natural gas pipes, $RC_{station}$ denotes the replacement cost of natural gas stations, $RC_{DS,CB,Buses}$ is the replacement cost of disconnect switches, circuit breakers and buses, and $RC_{Transformer}$ represents the replacement cost of transformers. Additionally, DP_{pipe} is the damage probability for natural gas pipes, $DP_{station}$ denotes the damage probability of natural gas stations, $DP_{DS,CB,Buses}$ is the damage probability of disconnect switches, circuit breakers and buses, and

$DP_{Transformer}$ indicates the damage probability of transformers. The total direct loss is estimated as the summation of natural gas and electricity direct losses as follows:

$$DL_{Total} = DL_B + DL_G + DL_E \tag{4.3}$$

4.3. Indirect Losses

Estimating indirect losses, as previously stated, involves a complex framework. Through the use of Input-Output (IO) modelling such losses can be estimated. The Egyptian IO table is produced by the Central Agency for Public Mobilization and Statistics (CAPMAS, 2006). The table reflects the interdependencies between the different economic sectors. Accordingly, in the event that such a sector is disrupted, the resulting damage to the other sectors can also be estimated. The framework for estimating such losses is described in Dorra (2011), and summarized in the points below:

1. Collect or develop Input-Output (IO) tables
2. Calculate the sector damage based on the physical damage in each sector. This is carried out by transforming the physical damage to the built environment and the lifeline networks into economic sector damage, based on the employment statistics within each district
3. Apply the damage to the IO economic sectors
4. Calculate the cost of recovery and time needed to recover the physical damage and the economy
5. Through the use of imports and exports bottlenecks in the economy can be reduced, thus maximising economic output. Accordingly, possible increases in imports and exports are applied to provide a means of economic resiliency
6. Money is injected into recovering the damaged economic sectors
7. If the economy has not fully recovered, Steps 5 and 6 are repeated

Since a difference exists between the total economic output when the economy is intact and when it is recovering, the total indirect loss in a given time period is estimated as:

$$Loss_i = GDP_i - Total\ Output_i \tag{4.4}$$

Since the recovery period can be extended, the total indirect loss is estimated as the summation of all indirect losses for all *n* recovery periods as shown in Equation (4.5).

$$Total\ Indirect\ Loss = \sum_{i=1}^{n} Loss_i \tag{4.5}$$

Through the use of this framework not only is indirect losses estimated, but a framework for optimising the recovery process is also established.

5. CONCLUSION

Most studies relating to damage resulting from earthquake occurrences have focused on only one aspect of the built environment. This overlooks the inherent dependencies that exist between each aspect of the built environment, and can underestimate possible economic losses by ignoring potential damage propagation. This study links the natural gas and electricity lifelines, providing a framework for modelling multiple lifeline damage. This framework is expandable with other lifelines possibly being included in future studies. Moreover, by linking the damage model to the economic model, the indirect losses which result from business interruption can be estimated. This provides a comprehensive loss model, whose framework can be used in any region.

REFERENCES

ADB (2007). Arab Republic of Egypt: 2007-2011 Country Strategy Paper. Regional Department North I, Arab Development Bank.

ADB (2009). Egypt Private Sector Country Profile. Arab Development Bank.

Anagnos, T. (2001). Development of an electrical substation equipment performance database for evaluation of equipment fragilities. *Report for Pacific Gas and Electric and Pacific Earthquake Engineering Centre*.

Badawi, H.S. and Mourad, S.A. (1994). Observations from the 12 October 1992 Dahshour earthquake in Egypt. *Natural Hazard* **10**:3, 261-274.

Boisvert, R. (1992). Indirect Losses from a Catastrophic Earthquake and the Local, Regional and National Interest. Indirect Economic Consequences of a Catastrophic Earthquake. Washington, DC. FEMA.

Brookshire, D.S., Chang, S.E., Cochrane, H., Olson, R.A., Rose, A., and Stenson J. (1997). Direct and Indirect Losses from Earthquake Damage. *Earthquake Spectra* **13**:4, 683-701.

Burrus Jr., R.T., Dumas, C.F., Farrell, C.H., and Hall, W.W. Jr. (2002). Impact of Low Intensity Hurricanes on Regional Economic Activity. *Natural Hazard Review* **3**:3, 118-125.

CAPMAS (2006). Egyptian National Census. *Central Agency for Public Mobilization and Statistics.*

CARANA (2002). Privatization in Egypt Quarterly Review April-June 2002. Privatization Coordination Support Unit, provided to the United States Agency for International Development.

Dorra EM (2011) Greater Cairo Earthquake Loss Assessment and its Implications on the Egyptian Economy. Imperial College London PhD Thesis.

EGAS (2007). Environmental and social impact assessment framework for Greater Cairo natural gas connections project. *Egyptian Natural Gas Holding Company.*

EGAS (2010). Local distribution of natural gas in Egypt. *Egyptian Natural Gas Holding Company.*

EIA (2010). Energy Overview of Egypt. *U.S. Energy Information Adminstration.*

Federal Emergency Management Agency, FEMA (2003). Instructional Material Complementing FEMA 451, Design Examples. Washington DC.

Khalifa, M., J. DaVanzo and D. M. Adamson. (2000). Population Growth in Egypt. RAND.

Ministry of Electricity and Energy (2009). Electricity Extension Report. Egypt.

Ministry of Finance (2010). Egyptian Quarterly Financial Report. Egypt.

Ministry of Petroleum (2010). Natural Gas in Egypt. *Report, Ministry of Petroleum 2010.*

Newmark, N.M. and Rosenbleuth, E. (1971). Fundamentals of Earthquake Engineering. Prentice-Hall, Inc.

Okuyama, Y. (2007). Economic model for disaster impact analysis: past, present, and future. *Economic Systems Research* **19**:2**,** 115-224.

Shinozuka, M., Dong, X., Chen, T.C., and Jin, X. (2007). Seismic performance of electric transmission network under component failure. *Earthquake Engineering and Structural Dynamics* **36**:2:, 227–244.

Song, J. and Ok, Seung-Yong (2009). Multi-scale system reliability analysis of lifeline networks under earthquake hazard. *Earthquake Engineering Structural Dynamics* **39**:3, 259-279.

St. John, C.M. and Zahrah, T.F. (1987). Aseismic design of underground structures. *Tunneling and Underground Space Technology* **2**:2, 165–197.

Torres-Vera, M.A. and Canas, J.A. (2003). A lifeline vulnerability study in Barcelona, Spain. *Reliability Engineering and System Safety* **80**, 205-210.

Zimmerman, R.D., Murillo-Sánchez, C.E., and Thomas, R.J. (2011). Matpower: Steady State Operations, Planning and Analysis Tools for Power Systems Research and Education. Power Systems, *IEEE Transactions* **26**:1, 12-19.