16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 927

*Registration Code: S-*X1464684957

SEISMIC RESILIENCE OF THE NEPALESE POWER SUPPLY SYSTEM DURING THE 2015 GORKHA EARTHQUAKE

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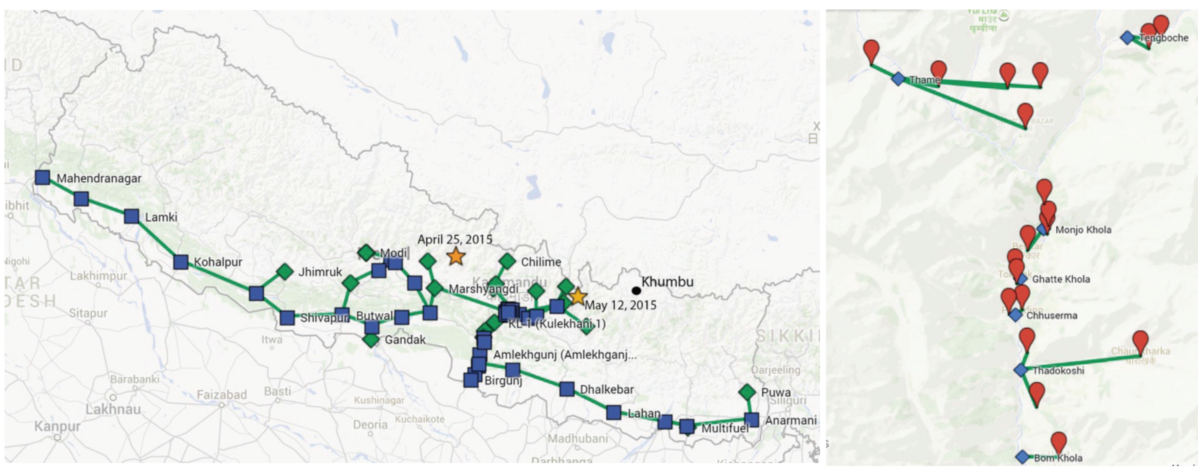
Abstract

More than 9000 people died, more than 22,000 people were injured and more than 750,000 buildings were destroyed during the 2015 Nepal Earthquake Series. A large part of the Nepalese cultural heritage was lost while the civil infrastructure systems suffered damage and experienced service blackouts. The aim of this study is to assess the seismic resilience of the Nepalese Electric Power Supply Systems (EPSS) using a compositional demand/supply resilience framework. Based on empirical data, obtained through on-site visits, expert interviews, report analysis, and different stakeholder inputs, the empirical *Lack of Resilience* (*LoR*) is computed. Vulnerability and recovery models for the Nepalese EPSS and building stock are developed and implemented in a simulation tool, allowing the computation of the expected *LoR* of the Nepalese on-grid system. Using the magnitude and epicenter of the April 25, 2015 Gorkha Earthquake, simulated curves for electric power supply capacity, demand and consumption are produced and compared to the empirical findings. The so developed and calibrated tool can be employed to assess the EPSS resilience during future earthquakes and to evaluate possible EPSS rebuilding and upgrading strategies.

Keywords: resilience; EPSS; 2015 Gorkha earthquake; recovery; vulnerability

1. Introduction

On April 25, 2015, Nepal was hit by a devastating M_w 7.8 earthquake. The epicenter was located in the Gorkha district, approximately 80 km north-west of Kathmandu, the capital of Nepal (Fig.1 (a)). The earthquake occurred on the border between the subducting Indian plate and the Eurasian plate on the Himalayan thrust [1, 2]. Multiple aftershocks hit the country, of which the most severe was on May 12, 2015 with a magnitude of 7.3 and an epicenter east of Kathmandu, near to the Kodari border crossing point to Tibet [3] (Fig.1 (a)). The earthquakes caused more than 9000 fatalities, 22,000 injuries and 750,000 buildings were damaged or destroyed [4]. Many schools, temples and heritage structures suffered irreparable damage. The extent of damage was not only due to the magnitude of the earthquake but also to the low seismic building construction standards in Nepal (e.g. the very weak traditional mud mortar rubble stone houses). Apart from the building stock, the civil infrastructure systems, including the Electric Power Supply System (EPSS), the water distribution system or the cellular telecommunication network, already running at their limits before the 2015 earthquakes, were damaged. The services provided by these systems played a crucial role in the emergency management in the aftermath of the earthquake, as well as in the coordination of the first early recovery tasks. Blackouts and shortages of these services had huge social, technical and organizational impacts on the community. It is, therefore, important to understand the behavior of civil infrastructure systems during and after the occurrence of a disaster. The study of the resilience of the Nepalese EPSS, made using a compositional demand/supply resilience framework, and the calibration of the framework to help predict consequences of potential future earthquakes in Nepal is presented in this paper.



(a) (b)

Fig. 1 - (a) Epicenters of the April 25 and the May 12, 2015 earthquakes and INPS system in Nepal (b) Off-grid power supply system in the Khumbu region (using map material from maps.google.com)

2. Compositional demand/supply resilience framework

The compositional demand/supply resilience framework (*Re-CoDeS*) allows the assessment of the seismic resilience of civil infrastructure systems [5, 6, 7]. A detailed explanation of the framework is given by Didier et al. [6]. It is composed by the following elements:

- The evolution of the supply of a civil infrastructure system over time, given by the seismic vulnerability of its components and their recovery after an earthquake disaster.
- The evolution of the demand for the services supplied by the civil infrastructure system.
- A system service model, regulating the production, transmission and distribution of the services of the civil infrastructure system and taking, for example, service allocation strategies of the system operator into account.

The resilience of a civil infrastructure system is defined in *Re-CoDeS* as its time-varying ability to cover the demand of the community for its services [6]. Therefore, the system shows a *Lack of Resilience* (LoR_{sys}) when the demand to the infrastructure system cannot be fully supplied. LoR_{sys} is given by:

$$LoR_{sys} = \sum_i LoR_i = \sum_i \int_{t_0}^{t_1} \langle D_i(t) - S_i^{av}(t) \rangle dt = \int_{t_0}^{t_1} (D_{sys}(t) - C_{sys}(t)) dt \quad (1)$$

where LoR_{sys} is the *Lack of Resilience* of the entire civil infrastructure system, LoR_i is the *Lack of Resilience* at node *i*, $D_i(t)$ is the demand at node *i* and time *t*, $S_i^{av}(t)$ is the available supply at node *i* and time *t*, $D_{sys}(t)$ is the demand to the entire system and $C_{sys}(t)$ is the consumption in the entire system at time *t*. $\langle \cdot \rangle$ is the singularity function and returns *0* if $D_i(t) - S_i^{av}(t) \leq 0$, and $D_i(t) - S_i^{av}(t)$ otherwise. t_0 and t_f are the start and the end of the resilience assessment period, respectively.

3. The Nepalese EPSSs

The Nepalese electric power supply can be divided mainly into two parts: the on-grid system, or the Integrated Nepal Power System (INPS), managed by the Nepal Electricity Authority (NEA) and a multitude of smaller, off-grid systems, mostly managed by local authorities or companies that supply power to communities in more remote or rural areas. The INPS contains all hydropower, thermal and solar power plants, which are directly owned by the NEA or by the Independent Power Producers (IPPs) and connected to the national supply grid of the country. IPPs are privately owned companies that produce electricity and feed it into the INPS network. Most power plants in Nepal have been financed and built in cooperation with other countries, for example Japan, Austria, China or India. The maximum nominal capacity of the entire INPS network is 782.55 MW [8, 9]. Table 2 lists all the major INPS-connected hydro and thermal power plants with their capacity.

The INPS experienced regular blackouts and load shedding before the 2015 earthquakes. During the entire year, but particularly so during the dry season in Nepal, the supply capacity of the network is not sufficient to meet the demand for power of the communities. The hydropower plants are mostly run-of-the-river plants whose performance is directly linked to the amount of flow of water in the respective rivers, as they do not have any, or only have limited, water storage capacities. Therefore, the NEA issues load shedding plans, which schedule planned blackouts for parts of the communities (usually several hours per day). Note that the duration of load shedding during the year before the 2015 Gorkha earthquake reached as much as 16 hours per day [10].

In addition to the INPS, many off-grid systems supply power to local communities. The National Planning Commission distinguishes between micro hydropower projects, solar home systems, small solar home systems and institutional solar PV systems [11]. An example for such an off-grid system is the system in the Khumbu region in the north-east of Nepal (district of Solukhumbu). This Himalayan region is not connected to the INPS and all villages upwards from Lukla are not reachable by car (e.g., Thame and Dingboche in Fig.1 (b)). The system contains several small hydropower plants that supply the surrounding villages. Their capacity ranges from 30 kW in Tengboche up to 620 kW in Thame. The power plants are mostly operated by residents of the surrounding villages and maintained in cooperation with NGOs. Depending on the available maintenance, many plants experienced significant capacity reductions before the 2015 earthquakes.

2. Resilience of the off-grid system in Khumbu

The performance after the earthquake of the power plants of the off-grid system in the Khumbu region was quite different. This is partly due to the fact that the power plants have different mechanical components and powerhouse designs, with different degrees of robustness. For example, the hydropower plant in Thame was financed and built in cooperation with the Austrian government and is, thus, using components and a powerhouse designed to Austrian standards. The damage degree and the recovery time of seven power plants visited during a field trip in October 2015 are summarized in Table 1.

Most powerhouses were damaged to some extent – from minor cracks in the walls or foundation of the powerhouse up to power house collapse in Monjo Khola and Tengboche. Since the villages upwards from Lukla are only reachable by foot, yak or helicopter, heavy components and equipment have to be carried by porters and/or helicopters to their respective destinations. In combination with the limited availability of those components in Nepal, this results in a very slow and delayed recovery process of more seriously damaged plants, compared to the process in developed countries (e.g. compared to the values given by Chang et al. [12]).

It is however difficult to compare the supply performance, the demand and the load shedding of the different plants, as many of them do not record the required data. At the other plants. the data is recorded manually in handwritten logbooks (only available at the plant itself), with a granularity varying from 30 minutes to 24 hours (e.g. only recording the daily peak load of the generator). After the earthquakes often no values have been recorded at all and the logs have large gaps, as the operators were busy to help in emergency actions in the community. The data gaps are, thus, too significant to conduct a meaningful resilience analysis. The present study will therefore be limited to the given overview of the off-grid EPSSs in Khumbu.

Table 1 - Visited off-grid hydropower plants in the Khumbu region

Name	Capacity [kW]	Data available	Damage	Shut-down time	Restore date	Connected villages
Bom Khola	100	Y	-	-	-	1
Thadokoshi	100	Y	-	-	-	4
Chhuserma	35	N	Cracks in powerhouse	1 week	02/05/15	5
Ghatte Khola	70	N	Cracks in foundation, penstock lines damaged	2 hours	25/04/15	3
Monjo Khola	50	N	Power house collapsed, equipment damage	Running, reduced performance	-	4
Thame	620	Y	Cracks in power house	-	-	5
Tengboche	30	N	Power house collapsed, generator destroyed, penstock lines damaged	6 months	25/10/15	2

4. Resilience of the INPS during the 2015 Nepal Earthquake series

The resilience of the INPS during the 2015 Nepal Earthquake Series was assessed using the compositional demand/supply resilience framework with empirical data. Data for the power demand was obtained for the period from April 14 to May 8 and from May 10 to May 16, 2015. For May 9 the demand was interpolated using the average demand of the three days before and after that date. Data for the load shedding, the power imports from abroad, and the power production (daily peak load and total production) was obtained for the period from April 14 to April 21, from May 1 to May 6, and from May 10 to May 16. For the missing days, the average imports and load shedding amounts from the previous days have been used. In addition to the numerical data, damage and recovery data for most power plants of the INPS was provided. The data for 19 major power plants is shown in Table 2. Using this data, it was possible to calculate the supply capacity of the INPS over time.

A permanent issue in Nepal is the lacking maintenance of the electric power systems. According to stakeholder interviews, many power plants cannot be run at their initial nominal capacity anymore, due to degradation related to ageing, combined with the lack of proper maintenance. Additionally, as most of the plants are hydropower plants and do not have any, or have only limited water storage capacities, the reduced water flow levels (at the end of the dry season, when the mainshock occurred) have a negative impact on the maximal achievable electric power production. The nominal values given by the NEA [9] need thus to be adapted in order to produce the actual supply capacity curve and to distinguish the damages that were already present before the 2015 earthquakes from the damages caused by the earthquakes. A capacity reduction factor that compares the (peak) energy production data available for 16 INPS hydropower plants before the earthquakes to their initial nominal capacity (i.e. the power plants listed in Table 2, excluding the two thermal plants and Gandak, which was out of operation when the earthquake hit the community) was calculated to model the reduced production capacity.

It is assumed that due to load shedding, the operators would run the power plants at their maximum available capacity in order to minimize the supply deficit. The supply capacity of the INPS might still be overestimated using this procedure, as some additional factors that reduce the supply capacity even further (e.g. strategic choices of the system operator) have not been considered in the model. Note that some power plants of the INPS are not in operation due to cost reasons, even though they are technically functional. This is, for example, the case for

"Multifuel" and the "Hetauda Diesel" stations, whose power production costs are quite elevated due to high fuel prices.

Applying the calculated reduction factor to the initial nominal capacities, the empirical production capacity of the Nepalese power system is computed using the damage and recovery data from the INPS network from Table 2. The daily amount of imported electricity is then added to the calculated production capacity in order to obtain the supply capacity. The average empirical demand is obtained by adding the amount of load shedding to the amount of consumed electric power (i.e. the produced plus imported electric power). The observed curves for the daily average supply capacity, demand and consumption are shown in Fig.2. The empirical data points are marked by asterisks on the curve.

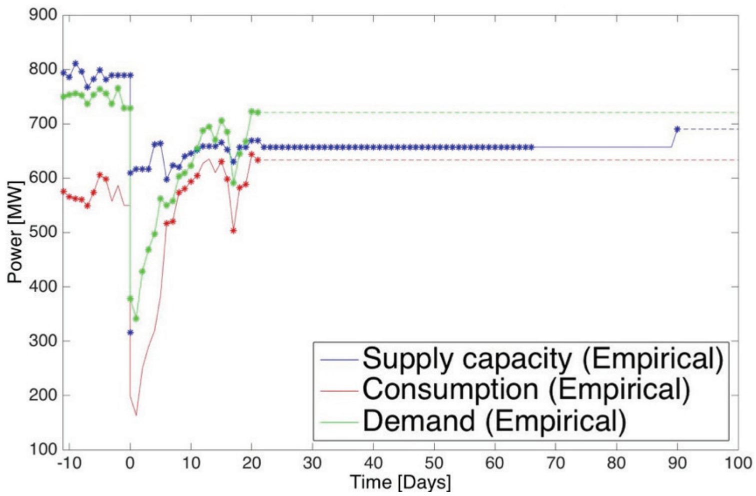


Fig. 2 - Observed average supply capacity, demand and consumption curves for the INPS

The pre-earthquake average supply capacity, including power imports to the system (on average around 4800 MWh per day), was around 790 MW. This indicates that the installed Nepalese power production capacity including the imports would be theoretically large enough to cover the entire demand to the INPS system, if the operators were able to run the system at its full capacity. After the April 25, 2015 mainshock, the average daily power supply capacity was reduced by about 60%, immediately followed by a fast increase back to around 75% of the pre-disaster supply capacity. The drop was due to damage as well as to the emergency shutdown of many power plants for safety reasons and for damage assessment. After verification of potential damages and minor repairs, 7 power plants were reconnected to the network within one day. Over the first 20 days after the earthquake, the supply capacity ranged between approximately 600 and 660 MW. These fluctuations were mainly due to the differences in the daily amount of imported power. The drop on the 18th day was due to the May 12, 2015 aftershock. It has to be noted that until today (April 2016), some power plants could not be fully repaired and, thus, the pre-disaster supply capacity could not be fully recovered. According to stakeholder interviews, major damage to plants that were under construction when the earthquake hit, will have a negative impact on the Nepalese EPSS for many more years.

The big drop in demand after the earthquake (from around 750 MW to less than 350 MW) and the subsequent fast recovery may not only be explainable by building damages and fatalities. Social and economic factors, such as the relocation of people and impacts on businesses and industrial production, play a crucial role in the demand for electric power. Damage to factories, reduced workforce (workers were killed in the earthquake or did not come to work since they were engaged in disaster reduction actions), and shutdowns of companies (for example to check the structural integrity of their production sites) reduced the electric power demand shortly after the earthquake. After 2 to 3 weeks, the demand was back to a level slightly below pre-disaster levels.

Finally, the observed electric power consumption in the INPS before the April 25, 2015 mainshock was between 550 and 600 MW. Since the consumption at each distribution substation is the smaller of available supply or demand, the consumption curve followed the demand and available supply curves. After a huge drop immediately after the April 25, 2015 mainshock, the consumption went back to levels higher than before the earthquakes. The second drop on May 12, 2015, which can also be observed in the service demand curve, is due to the M7.3 aftershock that hit Nepal that day. However, as no damage information is available for the aftershock, this assumption cannot be verified. It should be noted that the consumption levels after the earthquake are higher than the pre-disaster ones. This suggests that the INPS operators activated reserve capacities in the system (e.g. run the thermal power plants "Hetauda Diesel" or "Multifuel", not in operation before the earthquake due to economic considerations). In combination with the decrease in demand (due to building collapses, interruption of industrial production, etc.) the post-disaster *LoR* of the INPS actually decreased from the INPS operator's point of view, if compared to the *LoR*, observed before the earthquake. This result might be counterintuitive but was confirmed during stakeholder interviews and by empirical data, as load shedding could be reduced in the period after the earthquake events (from an average daily amount of 180 MW down to 60 MW). Due to the lack of detailed, complete and especially reliable numerical data, the exact *LoR*, using Equation (1), is not calculated here. However, the supply/demand resilience framework gives a good qualitative overview of the consequences of the earthquake and the impact on the resilience of the INPS.

Table 2 - Capacity and observed damage of the major power plants of the INPS

Name	Capacity [MW]	Damage	Shut-down time [h]	Restore date
Modi	14.8	Operation electric line problem	9	25/04/15
Marshyangdi	69.0	Minor damage	9	25/04/15
Middle Marshyangdi	70.0	No significant damage	12	25/04/15
Kulekhani 1	60.0	Crack in dam	9	25/04/15
Kulekhani 2	32.0	No significant damage	9	25/04/15
Sunkoshi	10.1	Canal bed crack about 700 m	2160	24/07/15
Devighat	14.1	Canal leakage of water	288	07/05/15
Trishuli	24.0	Canal leakage of water	288	07/05/15
Kali Gandaki (KG-A)	144.0	No significant damage (Cracks in left bank of water reservoir)	9	25/04/15
Gandak	15.0	No damage	-	-
Puwa	6.2	Lack of water	24	26/04/15
Multifuel	39	No damage	-	-
Hetauda Diesel	14.4	No damage	-	-
Jhimruk	12.0	No damage	-	-
Lower Modi	10.0	Minor damage	-	-
Chilime	22.0	No damage information available	1608	01/07/15
Indrawati-3	7.5	No damage information available	-	-
Bhotekoshi	45.0	Penstock damage	Ongoing	
Khimti	60.0	No damage information available	101	29/04/15

5. Simulation of the resilience of the INPS

The obtained empirical data, analyzed above, was used to calibrate a simulation tool, allowing the assessment of the seismic resilience of EPSSs in the compositional demand/supply resilience framework, and to adapt it to the setting in Nepal. The tool can then be used to analyze the resilience of the INPS during possible future earthquakes. To reach this goal, the vulnerability and the recovery of the INPS, as well as the vulnerability and the recovery of the demand in Nepal need to be modeled first.

5.1 Modeling of the INPS (supply capacity)

It is assumed that the fragility of the components of the Nepalese power plants and electric substations can be modeled using fragility curves developed for Western infrastructure. Many power plants have in fact been built in cooperation with other developed countries (e.g. Austria, Japan or China) and therefore the respective design, standards and components used in the partner country are usually employed. The electric substations and power plants are modeled in the simulation tool using circuit breakers, bus bars, generators and transformers. For the simulations two different types of electric substations are used: supply and distribution substations. The supply substations feed the supply produced by electric power generators into the network, while the distribution substations transform the electric power to lower voltage levels for the distribution on a building level. For the purpose of this study electric substations are modeled using a simplistic design: supply substations are designed with 3 bus bars and 7 circuit breakers with 2 generators connected to them; distribution substations have 3 bus bars, 11 circuit breakers, and 3 transformers [6]. For the generators, two damage states are distinguished: DS2 (corresponding to moderate damage) and DS3 (corresponding to extensive damage) and the respective fragility functions for small unanchored generation plants from *HAZUS* [13] are used. It is assumed that the capacity of the generators is reduced to 50% of its pre-disaster capacity in DS2 (e.g. due to malfunctioning of rotating parts or oil leakage) and to 0% in DS3. For the other components only a differentiation between the fully operational and the failed states are made, and fragility functions given by Shinozuka et al. [14] are employed.

For the simulation of the expected resilience of the Nepalese INPS, the network topology is modeled based on the INPS network map provided by the NEA [9]. The map includes 19 main power plants (i.e. all major hydropower plants, both NEA owned Thermal Power Plants as well as the 6 major hydropower plants operated by IPPs), 39 operating distribution substations as well as the connections between them. The approximate geographic locations of the different nodes were estimated using OpenStreetMap and GoogleMaps.

The provided data accounts only for the supply capacity of 668.96 MW out of the total nominal 782.55 MW capacity of the Nepalese INPS, as smaller power plants are not modeled. In order to keep consistency and comparability (in terms of capacity) between the provided empirical damage and recovery data, the remaining 113.59 MW are distributed among the 19 known power plants, relative to their size. This assures that the network modeled for the simulation has the same supply capacity as the real network. The capacity reduction factor, as calculated in Section 4, is applied to the obtained capacities in order to account for reductions in production capacity, already present before the earthquake.

Lognormal component recovery functions, conditioned on the initial post-disaster damage state, are assumed for the components of the EPSS [5]. The respective mean and standard deviation are calculated based on empirical data. Due to the large differences in the recovery time, the recovery process is divided into a short one for smaller damage, and a long one for larger damage. All damage repaired from April 25 to May 7 is categorized as smaller damage (i.e. DS2), and all damage repaired after May 8 is considered as more severe damage (i.e. DS3). The parameters calculated from the obtained empirical data are given in Table 3.

Table 3 - Mean and standard deviation of the lognormal component recovery functions for the EPSS

Initial Damage State of the component	**Mean**	**Standard Deviation**
DS2	3.36 days	4.30 days
DS3	273.5 days	133.94 days

5.2 Modeling of the building stock (demand)

The building stock is used as a proxy to model the evolution of the demand of the community for electric power. Damaged and collapsed buildings are expected to have a reduced (potential) power demand, compared to the undamaged ones. It is therefore necessary to model the structure and the vulnerability of the Nepalese building stock in order to compute the changes of the demand. Based on data from the Nepalese Central Bureau of Statistics [15] and taking into account the different construction and occupancy types, 10 different building types are distinguished as representative for the composition of the Nepalese building stock:

- Residential, including adobe, brick in mud, brick in cement, timber and reinforced concrete residential buildings
- Industrial, including small industries and medium/large industries
- Commercial buildings
- Critical buildings (non-commercial), including hospitals and schools

In order to describe the behavior of these building types when subjected to seismic loads, fragility functions are adopted for each type. NSET and Guragain [16, 17] provide damage matrices for the predominant building types in the Kathmandu Valley, giving the expected damage pattern as a function of the Peak Ground Acceleration (PGA). Starting from these damage matrices and using the maximum likelihood method [18, 19], lognormal fragility curves for partial damage (DS2) and complete collapse (DS3) are computed for for Nepalese adobe, mud bonded, cement bonded and RC frame buildings. The parameters of the computed fragility functions, expressing the probability of reaching a certain (or a more severe) damage state for a given PGA, can be found in Table 4. Fragility functions for timber houses are also needed. However, due to the lack of more information or performance data on Nepalese timber houses, the fragility functions for “wood, light frame (W1)” for moderate (DS2) and complete (DS3) damage from *HAZUS* [13] were used. This might however lead to a slight overestimate of the seismic performance of these buildings, as most Nepalese houses are not built in accordance with any seismic design code [20]. For hospitals, the BC fragility curves computed above are used, as brick in cement, or stone in cement buildings are the most common hospitals buildings in Nepal [21]. According to a survey on 700 public schools in the Kathmandu Valley, over 60% of the surveyed schools were built using traditional Nepalese construction techniques and were expected to behave very poorly during earthquakes [22]. The computed fragility functions for BM houses are, thus, used for schools. For small industries, the BC fragility curves were employed, as it is expected that most of small industries in Nepal are operated out of residential buildings or buildings with similar construction techniques. For medium and large industries, the RC4 curves were used. Larger industries often have enough financial capabilities to build buildings with a minimum degree of structural performance. Commercial buildings are buildings for “service or tourism” (e.g. restaurants, hotels) [11]. They have often a more representative function and implied safety levels, thus, the RC3 fragility functions are chosen. The building typology and fragility functions used in this study are summarized in Table 4.

Table 4 – Used building types: lognormal fragility functions conditioned on PGA, with median λ and log standard deviation ζ; lognormal recovery functions from DS2/DS3 with mean μ_{rec} [months] and standard deviation σ_{rec} [months]

Building type		**Typology**	**Fragility function DS2**		**Fragility function DS3**		**Recovery from DS2**		**Recovery from DS3**	
			λ	ζ	λ	ζ	μ_{rec}	σ_{rec}	μ_{rec}	σ_{rec}
Residential	Adobe	AH	-0.680	1.555	-1.200	0.889	11.943	10.589	23.886	21.177
	Brick in mud	BM	-0.350	1.467	-0.883	0.861	11.943	10.589	23.886	21.177
	Brick in cement	BC	-1.026	0.947	-0.284	0.827	11.943	10.589	23.886	21.177
	Reinforced concrete	RC3	-0.582	0.932	0.078	1.114	25.119	8.330	50.328	16.660
	Timber [13]	TH	-1.079	0.640	-0.051	0.640	11.943	10.589	23.886	21.177
Industrial	Small industries	BC	-1.026	0.947	-0.284	0.827	11.943	10.589	23.886	21.177
	Medium/large industries	RC4	-0.808	0.810	-0.197	0.989	25.119	8.330	50.238	16.660
Commercial		RC3	-0.582	0.932	0.078	1.114	25.119	8.330	50.238	16.660
Critical	Hospitals	BC	-1.026	0.947	-0.284	0.827	24.403	12.387	48.806	24.774
	Schools	BM	-0.350	1.467	-0.883	0.861	30.201	10.590	60.403	21.181

The number of buildings of each building type in each district, connected to the on-grid system, is estimated from data provided by different sources [23, 24, 25, 26]. It is assumed that for residential buildings, only those having electric lights are connected to the power system. All other building types are assumed to be fully connected. The average electric power consumption for a building of a certain building type is calculated using data from the NEA [9] and adapted in order to match the total electric power consumption in Nepal before the earthquake, as indicated by the empirical data. The post-disaster demand of the buildings of the different occupancy types is linked to the damage state of the buildings and calculated according to Table 5 (with $k_{res} = k_{ind} = 1$, $DRF_{c,res} = DRF_{c,ind} = 90\%$). A detailed explanation of the calculation of the post-disaster electric power demand can be found in Didier et al. [31].

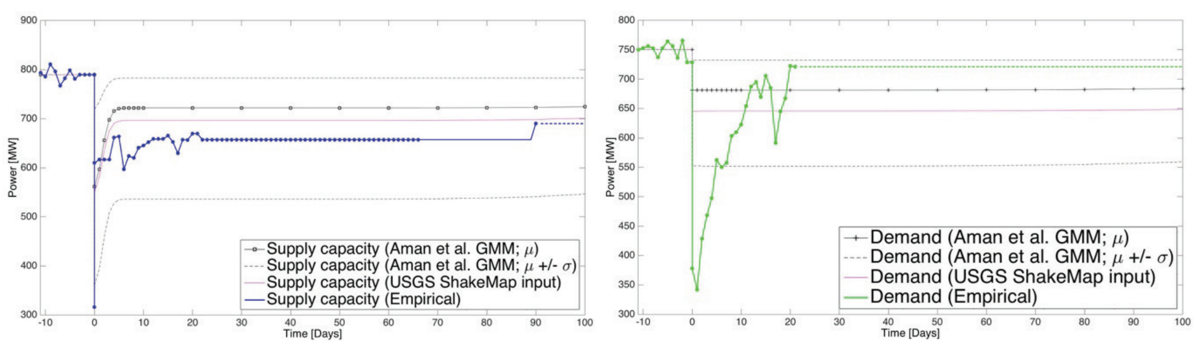
Table 5 - Potential post-disaster electric power demand for each damage state and occupancy type, as percentage of the pre-disaster demand [31]

Occupancy type	DS1	DS2	DS3
Residential	100%	$DRF_{c,res} * \left(1 - k_{res} * DRF_{l,res}\right) = DRF_{c,res} * (1 - k_{res} \frac{\#buildings_{DS3,local}}{\#\ buildings_{local}})$	0%
Industrial	100%	$DRF_{c,ind} * \left(1 - k_{ind} * DRF_{l,ind}\right) = DRF_{c,ind} * (1 - k_{ind} \frac{\#buildings_{DS3,total}}{\#buildings\ _{total}})$	0%
Commercial/Critical	100%	100%	0%

The government-driven recovery process, managed by the National Recovery Agency (NRA), has as of today (April 2016) not officially started. The first payouts of relief or reconstruction aid to people, whose homes were damaged or collapsed, are expected to be made from June 2016. Early rebuilding and repair efforts are thus limited to private initiatives. In particular, people in some rural areas have started to rebuild or repair their houses in the weeks and months after the earthquakes using their own funds. Due to the current lack of empirical data for Nepal, the recovery data, available from the 2005 Kashmir earthquake, was used as basis for the simulations [27, 28, 29]. Both disasters and both countries have similar characteristics (both earthquakes occurred on the fault between the Eurasian and Indian plate, similar earthquake magnitude and similar damage pattern). As the occupancy types given in [27, 28, 29] differ from the building types used for the simulations in Nepal, the recovery times of the best-coinciding building types are chosen. The parameters for the utilized lognormal building recovery functions are given in Table 4 [5]. They can be changed as soon as empirical recovery data for Nepal becomes available.

6. Comparison of the simulation results to the empirical findings

The resilience simulations for the modeled INPS and the built community are run for the epicenter and magnitude of the April 25, 2015 Gorkha earthquake. The expected values of the PGA at the sites of interest are computed in two ways: using the ground motion model of Aman et al. [30] and the USGS shakemap [1]. The observed INPS power supply capacity and power demand, as well as the simulated ones, using the initial losses with the mean and one-standard deviation bands of the PGA, are shown in Fig.3. Fig.4 (a) shows the same data for the simulated and the observed electric power consumption.

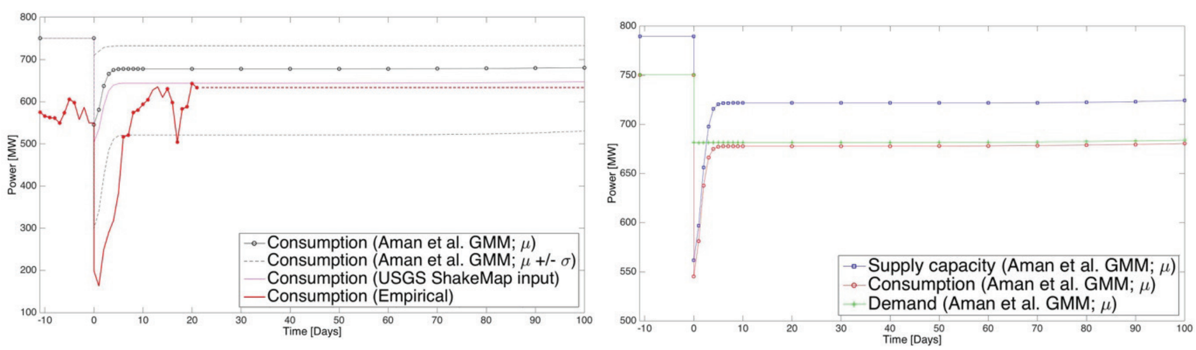


(a) (b)

Fig. 3 – (a) Comparison of the simulated and the empirical supply capacity curves (b) Comparison of the simulated and the empirical demand curves

Comparing the simulated and the empirical demand curves (Fig.3 (b)), one can see that the observed demand had a much larger initial drop than the simulated demand. The drop is even larger than the one obtained using the mean-plus-one-standard-deviation PGA values. This might indicate, that the damage of the building stock is not the only governing variable in the evolution of the demand during the disaster absorption phase. Especially in the first 2-3 weeks after the earthquake, the demand might have been additionally influenced by economic and political decisions (e.g. shut down of factories for some time after the earthquake) and the cultural setting of the country (e.g. many people in Nepal did not want to go back to their houses out of fear of aftershocks). After the end of the absorption phase, the empirical and simulated demand curves approach each other, with the empirical demand however stabilizing at a higher level. There might be two reasons for this: according to findings of a fieldtrip, many people in Nepal used (and are still using) partly damaged buildings (i.e. yellow/red tagged buildings), access to which would have been prohibited in more developed economies. Second, due to the small power consumption per capita, if compared to developed countries, the consumption difference between people living in their homes and peoples living in shelters might not be as high as assumed. Both reasons lead to a smaller reduction in power demand for the buildings in DS2 than supposed.

The simulations are in good agreement with the expected drop and the subsequent recovery of the supply capacity of the INPS (Fig.3 (a)). The larger initial empirical drop is especially due to the emergency shutdown of many undamaged power plants for safety reasons by the system operator. Such decisions of the operator are however not implemented in the simulation tool, but could be integrated into the network operation. The fluctuations of the empirical curve during the first days after the earthquake are caused by the variations in the amounts of electric power imported from abroad. A constant amount of imports is assumed in the simulations. In the longer term, the simulated supply capacity of the network is in good alignment with the empirical one.



(a) (b)

Fig. 4 – (a) Comparison of the empirical and simulated consumption curves (b) LoR using the ground motion model [30]

The observed electric power consumption in Nepal (Fig.4 (a)) shows a larger drop immediately after the earthquake, when compared to the simulated results, before recovering back to values higher than the pre-disaster consumption. The explanation for such large drop is the same as for the drop in demand, as the consumption is defined as the smaller of the potential demand and the available supply at each distribution node. If the demand decreases, the consumption decreases as well, while always remaining additionally limited by the available supply. After approximately 3 weeks, thus after the absorption phase, the simulated consumption is close to the empirical observations. Note that the empirical curves for the supply capacity, demand and consumption present a drop after the May 12, 2015 aftershock, which is however not included in the simulation tool.

Due to the lack of complete and verifiable empirical data, the following review is limited to qualitative aspects: the exactness implied by a calculated *LoR* using Eq. (1) with the available empirical data and simulation results cannot be guaranteed and might be misleading. However, when comparing the *LoR* computations (Fig.2 and Fig.4 (b)), some points need to be highlighted. First, note that the pre-disaster power consumption obtained by the simulation tool is too high compared to the actual power consumption. According to stakeholder interviews, this can be explained by the decision of the system operator not to use some power plants due to cost reasons before the earthquake. If the INPS was run at its full capacity, it would be possible to reduce the load shedding significantly and to supply a much larger demand, which would lead to a higher amount of consumed power (and thus a lower pre-disaster *LoR*). The network operation model used in the simulations does not include such decisions, as it was assumed that all power plants would be operated before the earthquake and would, therefore, contribute to the supply capacity. Thus, the simulation shows the best-possible pre-disaster situation. Subtracting the capacity of the idled plants would yield supply capacity values, closer to the observed pre-disaster situation in Nepal. It was however decided to not exclude the idled power plants from the simulations due to the lack of reliable information regarding the operators' network strategy. The second issue concerns the simulation of the demand curve. The simulated drop in demand is much higher than the drop that was observed after the earthquake, leading to a smaller simulated post-disaster *LoR* of the INPS. This issue can be overcome by employing for example Bayesian Probabilistic Networks (BPN) to estimate the demand of the different building types and of the community. Various technical, organizational and social parameters can be covered by a refined model. An example for a BPN in the context of the compositional demand/supply resilience framework is presented by Didier et al. [31]. Last but not least it has to be noted that the simulation results show the most discrepancies with respect to the empirical data during the absorption phase, i.e. the first weeks after the disaster. The simulation tool currently uses the same model for short and long-term resilience assessments. However, especially during the early absorption phase, many decisions made by the decision makers and the population, such as closing industries for protective measures, which are not necessarily directly linked to the observed damage and are currently not explicitly covered by the chosen modeling approach might govern the evolution of the potential power demand. Nevertheless, similar to the observed results, the simulated post-disaster *LoR* is smaller, when compared to the pre-disaster one. This can be again explained by the combination of a decrease of the power demand and an increase of the available supply after the earthquake (see Section 4). One of the observable consequences for this reduction of the *LoR* is the reduction in the amount of load-shedding in Nepal after the earthquakes.

7. Conclusion

An application of the compositional demand/supply resilience framework was presented for the Nepalese EPSS during the April 25, 2015 Gorkha earthquake. First, the *LoR* was qualitatively estimated using the empirical input obtained from different stakeholders in Nepal. The results of the simulations largely coincided with the observations made after the earthquake: the load-shedding decreased, indicated by the smaller post-disaster *LoR* of the INPS compared to its pre-disaster *LoR*. Based on the empirical data, a vulnerability model for the Nepalese EPSS and building stock was developed and implemented in a resilience simulation tool allowing to simulate the expected EPSS *LoR* in seismic events. Using the magnitude and the epicenter of the April 25, 2015 Gorkha earthquake, simulated curves for electric power supply capacity, demand and consumption were produced. They are in good agreement with the empirical data in the medium and long term after the earthquake. Immediately after the earthquake, during the absorption phase, the damage to the building stock and the components of the EPSS seem not to be the only variables that influence the operation of the EPSS and the electric power demand. Social, economic and political decisions are likely to have an impact on the results, however the current simulation tool does not incorporate their effects. Nevertheless, the demand/supply resilience framework and the simulation tool can be very useful to the EPSS system operator to assess the resilience during future earthquakes and to evaluate possible repair and upgrading strategies for the EPSS.

8. Acknowledgements

The authors gratefully acknowledge the funding for this project provided by the State Secretariat for Education, Research and Innovation (SERI) and Cooperation & Development Center (CODEV) FLASH research program as well as the assistance received from Nepal Electricity Authority (NEA), National Society for Earthquake Technology (NSET), Institute for Social and Environmental Transition-Nepal (ISET-Nepal) and the officials from off-grid communities in the Khumbu region. The findings and opinions stated in this paper are those of the authors: they are not necessarily condoned or shared by the funding agency or the collaborating agencies and individuals in Nepal.

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