5 July 2024
@ETH Zürich

# The impact of reserve power sources on vulnerability and restoration from disaster with interdependence of power and road networks

Hiroe ANDO, Kumamoto University

Takahiro Takeichi, Kumamoto University

# Backgrounds

- Disasters, accidents and terrorism can destroy the infrastructure that supports society.
- When one infrastructure is damaged in a disaster, adjacent infrastructures are often affected as well. Interdependence among infrastructures is important.

**Independencies of infrastructure networks**

✓Power supply NW
✓Transportation NW
✓Communication NW
✓Natural gas NW
✓Water supply NW

- Utne et al. (2011) and Kjølle et al. (2012)  analyzed the case of an electrical cable breakdown in the neighborhood of the Oslo central station in 2007, disrupting railway traffic for 20 hour and the telecommunications system for 10hours.
- There are many other examples of interdependence between infrastructures. (e.g. Dormady  and Ellis ,2018; McDaniels  et al., 2007)

# Backgrounds

The integration of electric power and transportation infrastructures will increase with the spread of electric vehicles (EVs) and renewable energy.

- Transportation : road network
- Electricity : power supply network

**An example of small-scale power use during disasters**

September 2019  Typhoon 15th in Japan

During a power outage, a family of four lives for about 2.5 days on a 24kWh EV

**Objective**

Verify the impact of reserve power sources by connectivity considering network interdependence of transportation and power in the event of a disaster

**Measures**

- Describe the interdependence of transportation and power networks in the disaster
- Evaluate connectivity based on the deployment and operation of reserve power sources in Kuma village with a history of disaster

# Road and Power Distribution

- Evaluation model on the respective infrastructure network
  - ✓ Road Network Connectivity
  - ✓ Power Supply Network

- Interdependencies between infrastructure networks
  - ✓ **Spatial Interdependencies**

    When a link is damaged, nearby links in different infrastructures are also damaged.
  - ✓ **Functionality Interdependencies**

    One infrastructure needs another to function

    In this study…
    - ➢ Disaster prevention sites with power outage cannot function.
    - ➢ Links that do not receive power have increased travel time due to disruption caused be signal failures, etc.

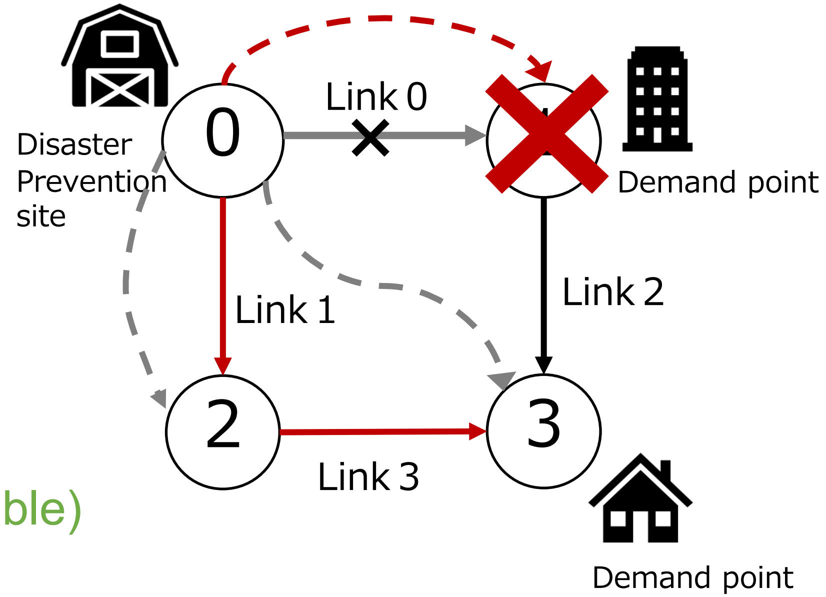
# Road and Power Distribution

- Evaluation model on the respective infrastructure network.
  - ✓ Road Network Connectivity
  - ✓ Power Supply Network

# Road network connectivity

- Whether the demand points (residence) and the any of disaster prevention sites are connected
- How many people are connected to which disaster prevention site by minimizing the total travel time?

Flow with excess link $t_a = M$ means unreachable



Total travel time minimization with excess links

$$\min_{x} \sum_{a} \underline{t_a}\,\underline{x_a}$$

Traffic volume of link $a$ (unknown variable)

Travel cost of link $a$

subject to

$$\sum_{a\in In(n)} x_a - \sum_{a\in Out(n)} x_a = \begin{cases} -\sum_n d_n & if\ n = \underline{r} \\ \underline{d_n} & \forall n \in \mathbf{N}|r \end{cases}$$

Origin node

Demand volume of node $n$

Each node receives a flow equal to demand volume

$$0 \le x_a \le c_a \ \ \forall a \in \mathbf{A} \cup \mathbf{A}_e$$

Capacity constraint

$$t_a = M, \forall a \in A_e$$

Travel cost of excess links is too large

# Power supply network

Maximise the total power flow to supply each demand point

$$\max_{x} \sum_{r} \sum_{a \in Out(r)} x_a$$

Maximise the total power flow from all power plants

subject to

$$0 \leq \sum_{a \in In(i)} x_a - \sum_{a \in Out(i)} x_a \leq v_i \; \forall i \in \mathbf{I}|r,$$

The amount of power received at the demand point is less than demand volume

$$\sum_{a \in Out(r)} x_a \leq k_r \; \forall \mathrm{r} \in \mathbf{R},$$

Power volume that each power plant can generate

$$0 \leq x_a \leq c_a, \forall a \in \mathbf{A}$$

Line capacity constraint

$x_a$ : Power flow on link $a$
$\mathbf{I}$ : Set of nodes
$\mathbf{R}$ : Set of power plant nodes
$r$ : Power plant node
$c_a$ : Capacity of link $a$
$k_r$ : Capacity of power plant $r$
$\mathbf{A}$ : Set of links

# Interdependency

## ○Interdependencies between infrastructure networks

- Immediately after the disaster
  - Disaster prevention sites that do not receive power will not work
  - Disruption of traffic control, such as traffic signals, increase travel times (vehicle speeds decrease) on links where power does not reach.
- Restore power and elimination of road obstacles
  - Impossible to restore power to link not connected by road network

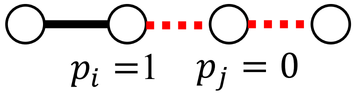
## ○Conditions for link restoration

- Power link can only be restored where is a road link.
- Let $K$ be the distance of roads that can be restored in 1 phase (time period).

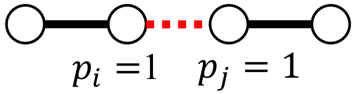
$p_i$: 1 if any of the links to a node are functioning, 0 if all are disrupted.

$$distance_e \le \begin{cases} 0, & if\ \ p_i + p_j = 0 \\ K, & if\ \ p_i + p_j = 1 \\ 2K & if\ \ p_i + p_j = 2 \end{cases} \qquad \forall (i,j) \in e$$

Only one node is connected



Both nodes are connected



Link $e$ satisfying this equation can be restored within 1 phase

# Application

Kuma Village, Kumamoto Prefecture in Japan, which was severely flooded in the past

**Road network**

362 links, 146 nodes

4 disaster prevention sites (designated evacuation place)

**Power supply network**

Created based on utility pole location data

178 links, 150 nodes

**Demand**

- 1883 people by population data in 2023
- Power demand of each node is calculated from the power demand of village unit in 2022 according to the percentage of population

**Restoration**

1 phase is 12 hour

The length of road link that can be recovered $K$ in 1 phase is 250m

# Disaster Scenario and Application

**Disruption links by the rainfall history in July 2020**

Road and power network : Flooding depth of 3m or more

Road network only : cave-in occurred on the road

Archive Kuma Village

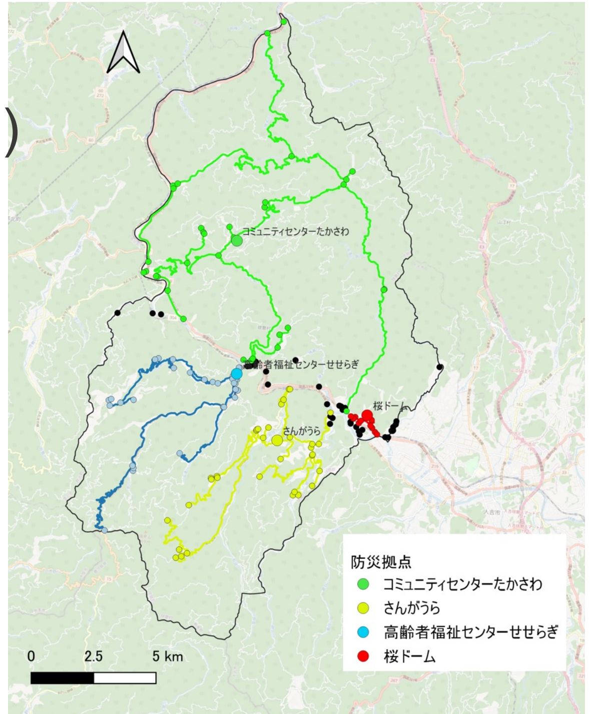
**The number of isolation people**

- Road : 556 people (222 of them are in the flood zone)

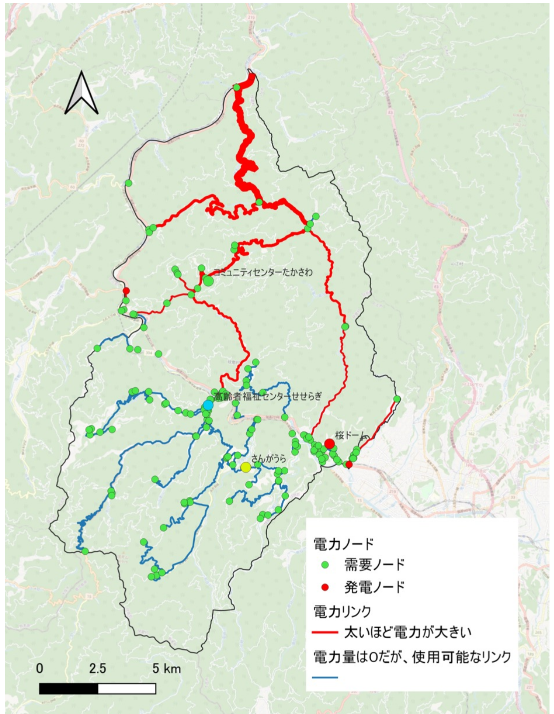
Many isolated in flooded areas and along the river

- Power outage : 1385 people

All bridge links over the Kuma River were destroyed, disrupting the power supply to all nodes on the south side, resulting in a large number of people without power



Road network



Power network

# Reserve power source

## Assume that electric vehicles (EVs) are used as a **reserve power source** in a disaster

New power plants with smaller capacities are added to the power supply model

### Application to Kuma Village

- Setting of EVs
  - ✓60kWh standard EV
  - ✓Emergency power requirement is 1/3 of dairy power consumption

| Case | Deployment | | Operation | | Number of EVs installed | | |
|---|---|---|---|---|---|---|---|
| | Disaster prevention sites | Demand point | Use only where deployed | Flow to other locations | 3 | 40 | 120 |
| 1 | ✓ | | ✓ | | ✓ | | |
| 2 | ✓ | | | ✓ | ✓ | | |
| 3 | | ✓ | ✓ | | | ✓ | |
| 4 | | ✓ | | ✓ | | ✓ | |
| 5 | | ✓ | ✓ | | | | ✓ |
| 6 | | ✓ | | ✓ | | | ✓ |

- The current EV penetration rate applied to Kuma Village is 40 vehicles.
- 3 EVs are assumed to be managed by the government

# Interdependency

**○Interdependencies between infrastructure networks**

- Immediately after the disaster
  - Disaster prevention sites that do not receive power will not work
  - Disruption of traffic control, such as traffic signals, increase travel times (vehicle speeds decrease) on links where power does not reach.
- Restore power and elimination of road obstacles
  - Impossible to restore power to link not connected by road network

# Results (24h after disaster)

**Road**
Covered population
(number of nodes)
**1883(146)**

**Power**
Covered population
(number of nodes)
**1883(150)**

Disaster Occurrence

**Road**
**1188(101)**

**Power**
**498(36)**

Complete Isolation **589**

Power Outage

Power outage shut down several disaster prevention sites

**Road**
**456(32)**

**Power**
**498(36)**

Complete Isolation **1321**

| Reserve power source in operation | Covered population (number of nodes) | Complete Isolation |
|---|---|---|
| 3 EVs in sites<br>*Restoration of site functionality | Road 1327(101)<br>Power 498(36) | **450** |
| 3 EVs flow from sites | Road 456(32)<br>Power 590(74) | **1229** |
| 40 EVs in nodes | Road 456(32)<br>Power 764(63) | **1055** |
| 40 EVs flow from nodes | Road 456(32)<br>Power 822(109) | **997** |
| 120 EVs in nodes | Road 456(32)<br>Power 1130(66) | **689** |
| 120 EVs flow from nodes | Road 456(32)<br>Power 1610(40) | **209** |

*Completely Isolation: No connection to either the disaster prevention site or the power plant node

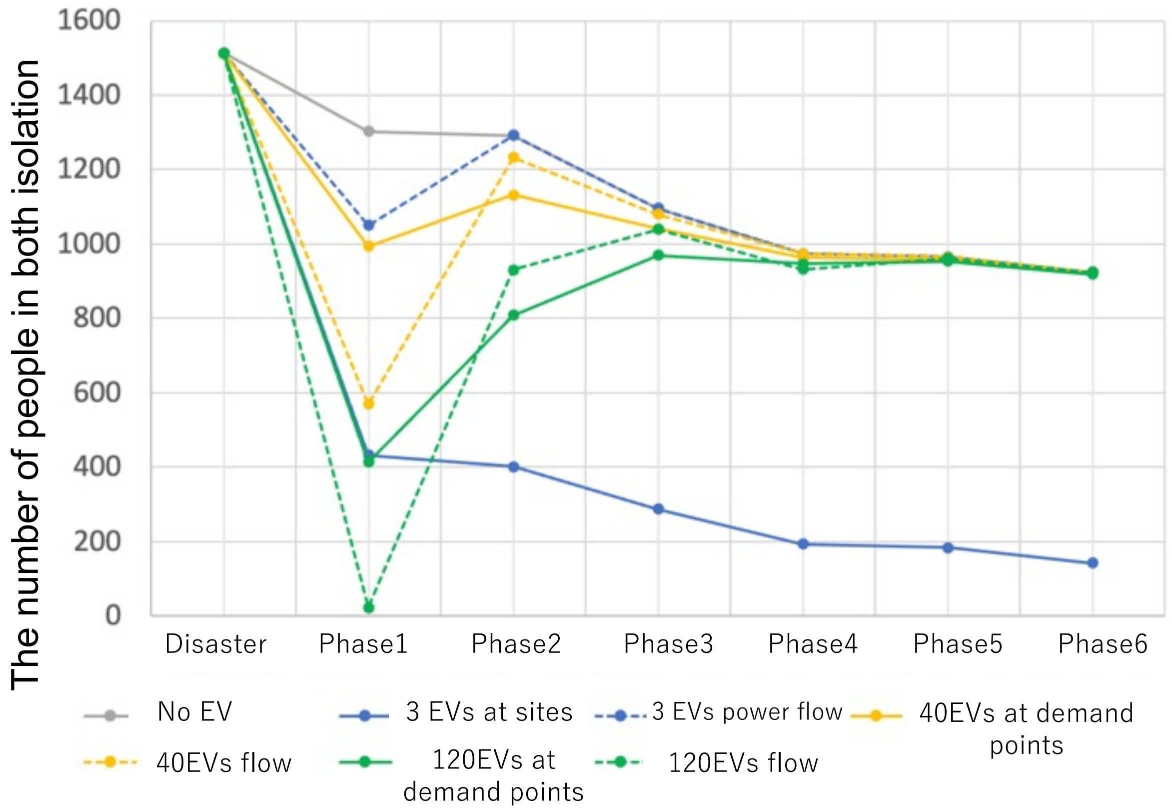
# Interdependency

○**Interdependencies between infrastructure networks**

- Immediately after the disaster
  - Disaster prevention sites that do not receive power will not work
  - Disruption of traffic control, such as traffic signals, increase travel times (vehicle speeds decrease) on links where power does not reach.
- Restore power and elimination of road obstacles
  - Impossible to restore power to link not connected by road network

# Results (including restorations)

- 1 Phase is defined as 12 hours



- Only when used with disaster prevention site only, the number of completely isolated people is gradually reduced.
- Other cases use up EV power and the number of fully isolated people increases again in Phase 2, but then gradually decreases during the recovery process

# Results (including restorations)

Case of 3 EVs in disaster prevention sites only

- Power volume used at disaster prevention sites

| **Time Lapse (h)** | **Unavailable links** | **Outage people** | Amount of electricity remaining in each base | | | |
|---|---|---|---|---|---|---|
| | | | **Base1 Seseragi** | **Base2 Sangaura** | **Base3 Sakura dome** | **Base 4 Takasawa** |
| Before disaster | 0 | 0 | 180 | 180 | 180 | 180 |
| Phase 1 (0~12) | 49 | 1385 | 180 | 180 | 180 | 180 |
| Phase 2 (12~24) | 43 | 1371 | 147.95 | 131.9 | 133.45 | 180 |
| Phase 3 (24~36) | 36 | 1358 | 115.9 | 99.85 | 101.4 | 180 |
| Phase 4 (36~48) | 21 | 1123 | 83.85 | 67.8 | 69.35 | 180 |
| Phase 5 (48~60) | 17 | 1042 | 51.8 | 35.75 | 69.35 | 180 |
| Phase 6 (60~72) | 16 | 1011 | 19.75 | 3.7 | 69.35 | 180 |

- Usage varies depending on the disaster prevention site.
- Base 4 has no power outages at the surrounding area and is not used at all
- Consideration should be given to using the characteristics of EVs to move to other disaster prevention sites if the road network is connected.

# Conclusions

- The interdependence of road and power network during disasters was described and the impact was evaluated using a connectivity model.
- Connectivity was evaluated for Kuma village using the actual disaster records, and the change in the number of isolated people due to the introduction of EVs was verified.
- Effective deployment of EVs differs depending on the location, number of EVs installed, and operation (with or without power flow from EVs).
- When a small number of EVs are installed only at disaster prevention sites, limited use to these sites is highly effective.

## Future plans

- Measuring the effectiveness of EV buses for school commuting introduced in Kuma Village
- Consider that EVs can be mobile depending on the state of road network connectivity
- Optimization problem of the type, number, and placement of EVs to reduce complete isolation of both power and road network.