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Improving V_{S30} Mapping in the Taipei Basin: Correlating Soil Parameters with Shear-Wave Velocity and Analyzing Extrapolation Methods

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Introduction

Aims:

- Use borehole data within the Taipei Basin to improve shear-wave velocity transformation functions.
- Analyse extrapolation methods to include shallow borehole data in V_{S30} map.
- Use Kriging with varying local means to produce the improved V_{S30} map for the Taipei Basin.

Why in the Taipei Basin:

- The Taipei Basin is particularly susceptible to earthquake risks due to its high population density and local geology.
- Site effect - presence of soft sediment deposits overlaying hard rock, causing shear-waves to amplify and resulting in intensified seismic ground motion.
- Large database available in this area, including many engineering boreholes and strong motion stations.

V_{S30}

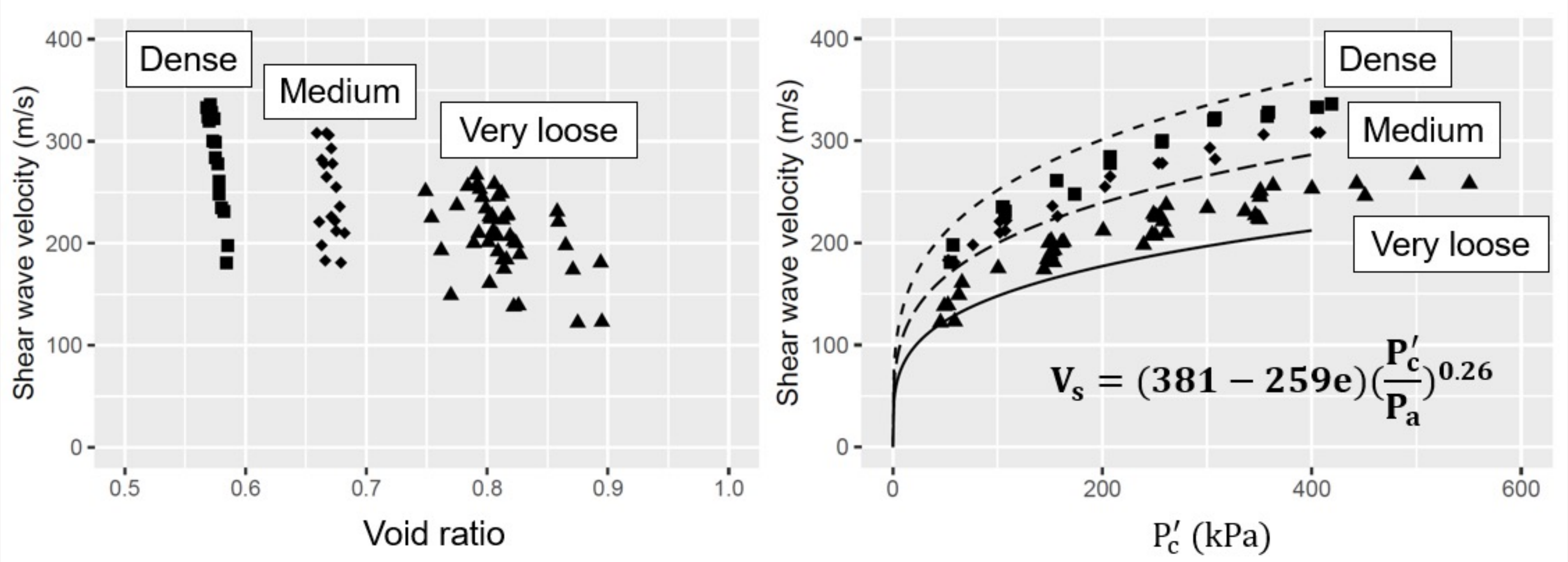
- The time-average shear-wave velocity within the top 30 meters of the ground (V_{S30}).
- V_{S30} mapping is critical in providing site-specific hazard assessments.
- Recent approaches to V_{S30} mapping mostly involve a combination of geophysical surveys, geological investigations and empirical models
- However, these approaches can have significant uncertainties due to low borehole densities, insufficient data and inconsistent empirical equations.

Site Class	Range of V_{S30} (m/s)	Description
A	$V_{S30} > 1500$	Hard rock
B	$900 < V_{S30} \leq 1500$	Medium hard rock
BC	$640 < V_{S30} \leq 900$	Soft rock
C	$440 < V_{S30} \leq 640$	Very dense sand or hard clay
CD	$300 < V_{S30} \leq 440$	Dense sand or very stiff clay
D	$210 < V_{S30} \leq 300$	Medium dense sand or stiff clay
DE	$150 < V_{S30} \leq 210$	Loose sand or medium stiff clay
E	$V_{S30} < 150$	Very loose sand or soft clay

V_{S30} site classification standards (Modified from BSSC, 2020)

V_s Transformation Functions

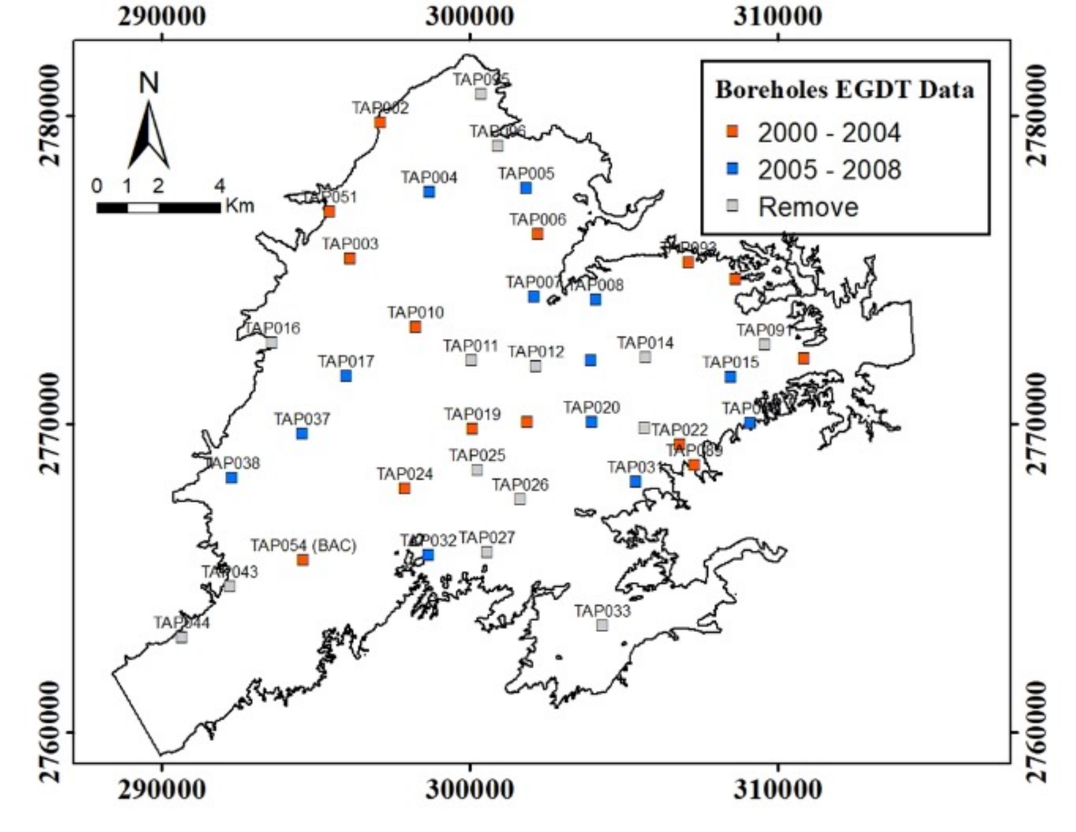
- Correlation between shear-wave velocity, void ratio (e), and effective stress (σ')
- Void ratio is a measure of how compact or porous a soil is, and therefore soils with lower void ratios will be denser and have higher shear-wave velocities.
- Whereas effective stress accounts for pressure between soil particles. Higher effective stress increases this pressure, resulting in stiffer and stronger soils, which leads to higher shear-wave velocities.



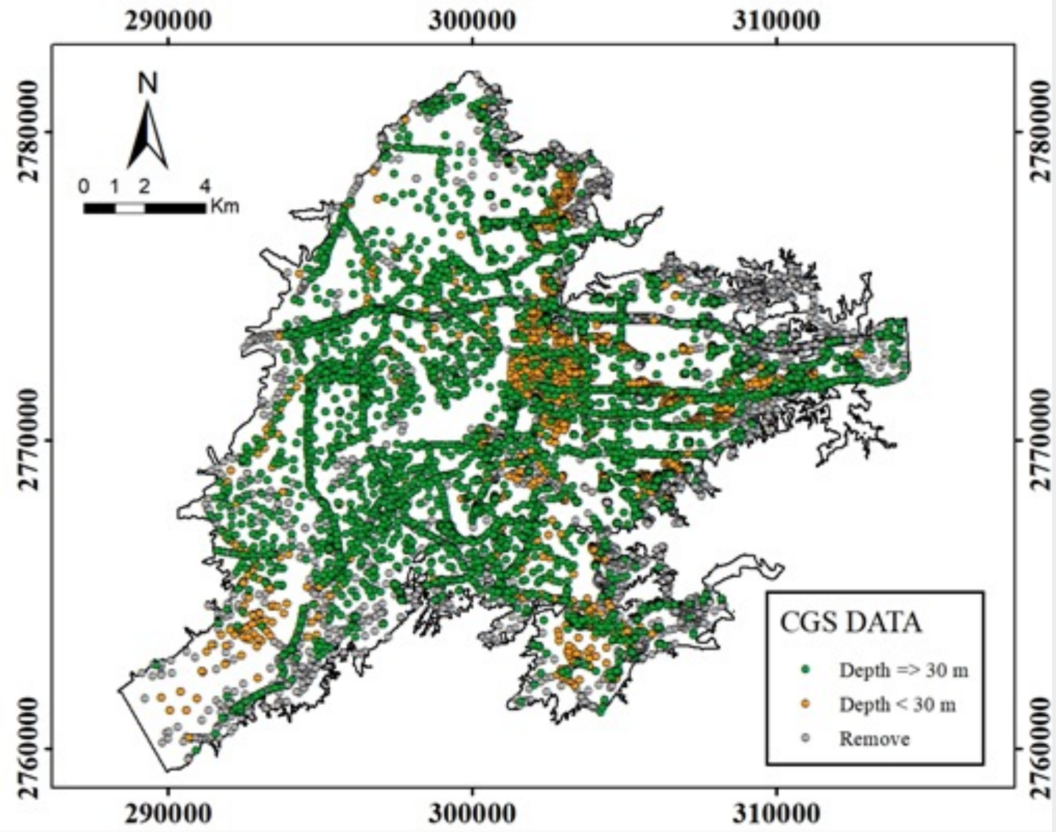
Modified from Robertson et al. (1995). (Pa = 100 kPa)

Databases

Engineering Geological Database for the Taiwan Strong Motion Instrumentation Program (EGDT)



Central Geological Survey (CGS) Database

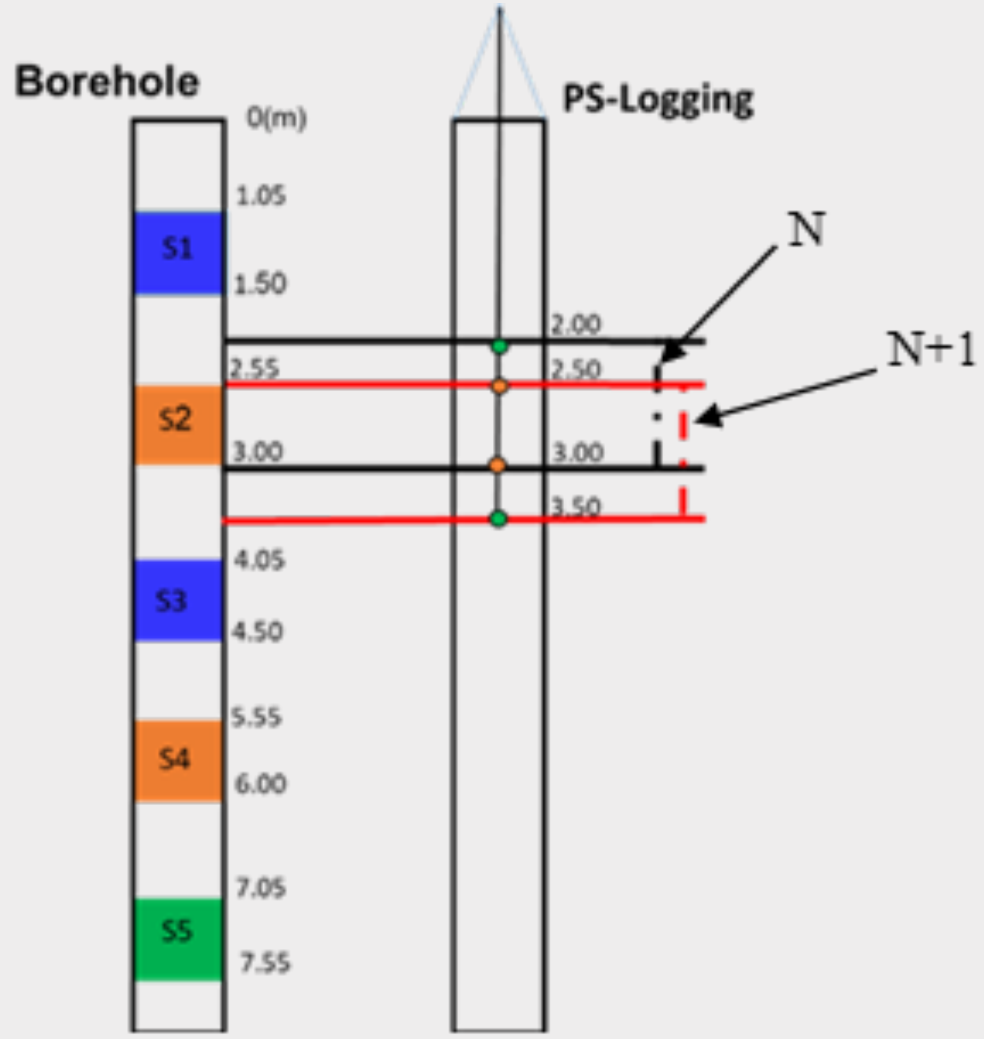


Quality check of shear-wave velocity data

- cross-correlation analysis – assesses signal symmetry.
- visual inspection – clarity of the initial waveform.
- Class A (good), Class B (moderate) or Class C (poor).

Pairing soil parameters with shear-wave velocity measurements

- Soil sampling is conducted at 1.5-meter intervals with a depth increment of 45 centimeters each time.
- Velocity measurements are taken at 1-meter intervals with a depth increment of 0.5 meter each time.
- A total of 702 data pairs were obtained, which will be utilized for the subsequent regression analysis.



Soil Parameters

Void ratio $$e = \frac{(w+1)G_s \cdot \gamma_w - \gamma_t}{\gamma_t}$$

where w is the water content, G_s is specific gravity, γ_w is the unit weight of water (9.807 kN/m^3), and γ_t is the unit weight of soil (kN/m^3).

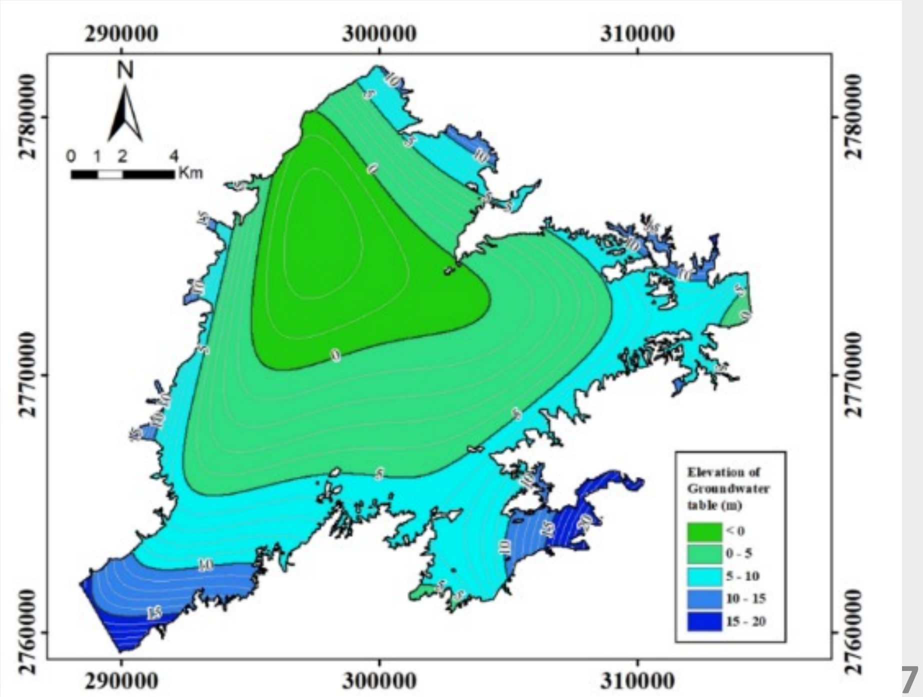
Vertical effective stress
$$\sigma'_v = \sigma_v - u$$
$$\sigma'_v = \Sigma Z_i \gamma_i - u = \Sigma(Z_i \gamma_i) - [(Z_A - Z_W)\gamma_w]$$

where Z_i is the height of each soil layer, γ_i is the unit weight of that layer, Z_A is the depth of the borehole, and Z_w is the depth of the water table.

Information required:

1. Total unit weight of soil layers
2. The boundaries of each layer
3. The position of the groundwater table at the drilling location

Elevation of groundwater table



Estimation of shear-wave velocity for gravel, sand, silt, and clay

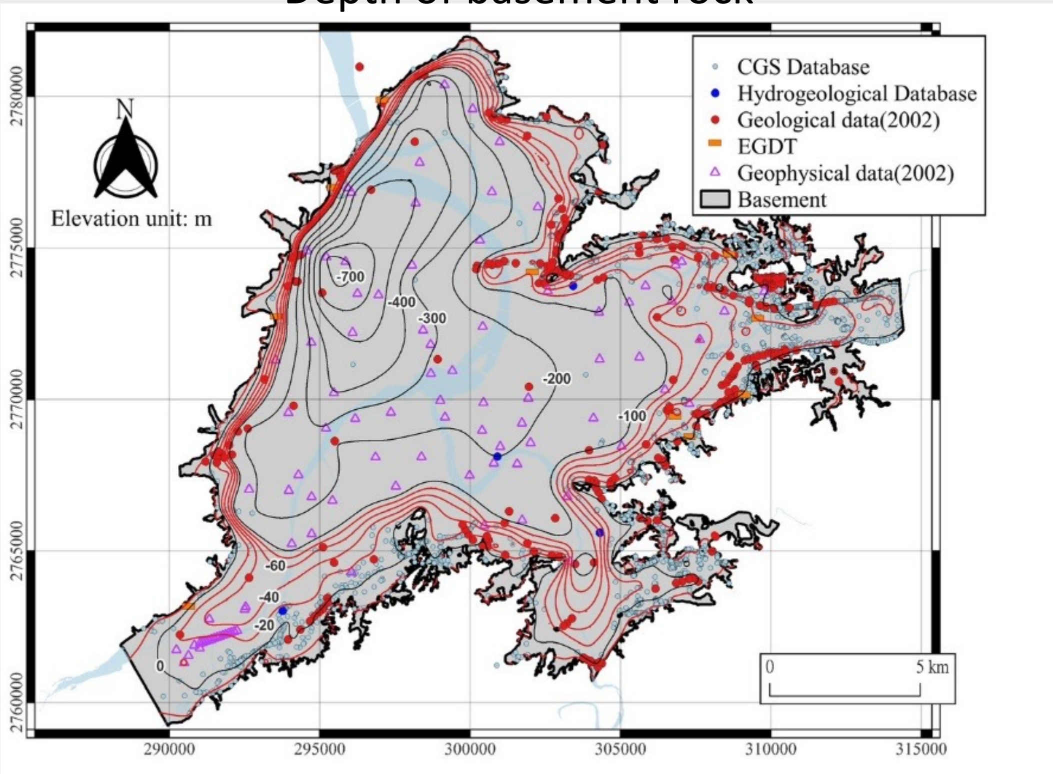
$$V_s = (m_1 - m_2 \mathrm{e})(\frac{\sigma_v'}{P_a})^{n_a}$$

where m_1, m_2 and n_a are regression coefficients, e is void ratio and σ_v' is effective vertical stress. Pa represents atmospheric pressure and is set to a constant value of 100 kPa

Estimation of shear-wave velocity for rock

- Average velocity of 697 m/s as an approximate value.
- This value is derived from the average shear-wave velocity in weathered and fresh upper Neogene rocks within the Taipei Basin.

Depth of basement rock



Lin (2023)

V_{S30}

EGDT, shear-wave velocity measurements are directly available at different depths, allowing the calculation of V_{S30} by summing the product of each V_S value and its corresponding thickness within the top 30 meters.

CGS boreholes only provide physical parameters of the strata, and therefore empirical relationships are employed to first estimate the V_S to 30 meters, and then subsequently V_{S30}.

$$V_{S30} = \frac{30}{\sum_{i=1}^{n} \frac{d_i}{V_{Si}}}$$

where n is total number velocity pairs, d_i and V_{Si} represents the thickness and shear-wave velocity at the ith layer.

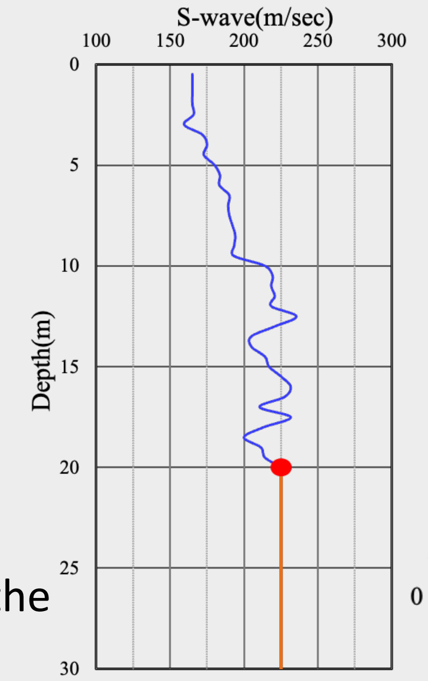
(The depth interval from 0 to 30 meters was divided into 30 equal segments, each representing a 1-meter depth increment)

Shallow Borehole Extrapolation

1. **Bottom Constant Velocity (BCV) model** - assumes that the shear-wave velocity remains constant from the depth of the shallow boreholes (Zp) to 30 meters.

$$V_{S30} = \frac{30}{\Delta t_z + \frac{30 - z_p}{V_{S(z_p)}}}$$

where z_p is the depth of the V_S profile and Δt_z is the shear-wave travel time from z_p to the surface.

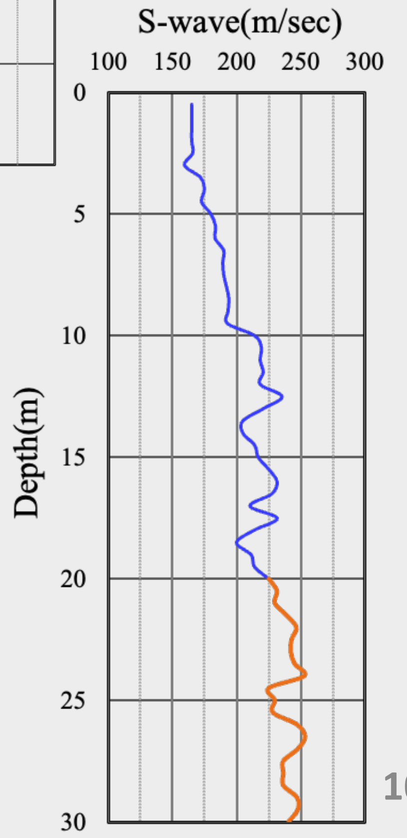


2. **Conditional Independent Property (CIP) model** - considers the potential variability using the correlation between the shear-wave velocity at a specific depth (V_S at Z_p) and the average velocity from that depth to 30 meters ($V_{S[zp,30]}$).

$$lo\ g\ V_{S[Z{\cdot}p30]} = c_0 + c_1 \log V_{S(z_p)}$$

$$V_{S30} = \frac{30}{\Delta t_z + \frac{30 - z_p}{V_{S[z_p,30]}}}$$

where c_0 and c_1 are regression coefficients



V_{S30} map: Kriging with varying local means

This technique combines direct shear-wave velocity measurements, which serve as the primary variable, with indirect shear-wave velocity values derived from transformation functions, as the auxiliary variables.

The spatial interpolation process consisted of three main steps:

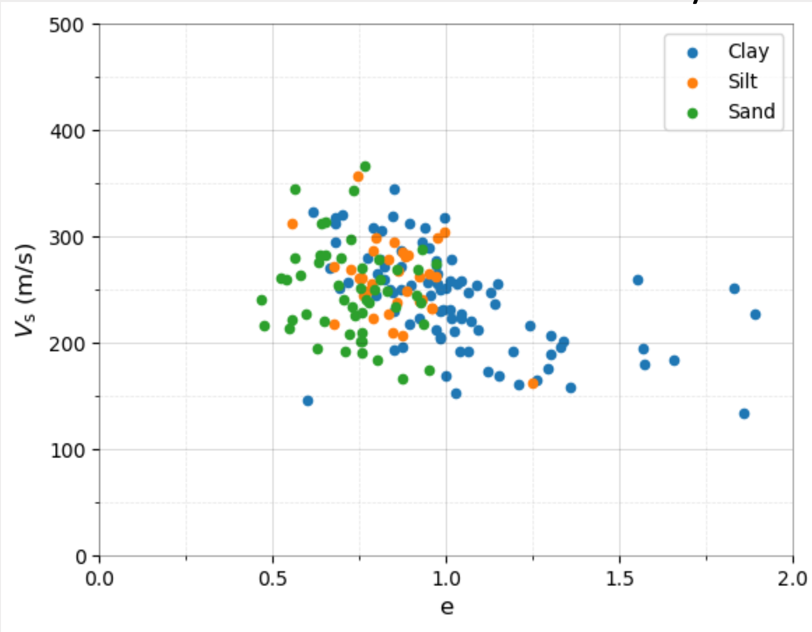
1. **Step 1: Kriging interpolation of auxiliary variables** - The V_{S30} values obtained from the CGS data were interpolated using Kriging.
2. **Step 2: Residual calculation and interpolation** - The residual value was calculated by subtracting the measured V_{S30} values from the EGDT data (primary variable) at the strong motion station borehole's corresponding location, from the grid value of the auxiliary variable. Kriging was then applied to generate a map of residual values.
3. **Step 3: Development of V_{S30} map** - The results obtained from the residual interpolation (step 2) were added back to the auxiliary variable grid (step 1). This produced the final distribution of V_{S30} obtained through Kriging with varying local means.

Shear Wave Velocity – Soil Parameter Correlation

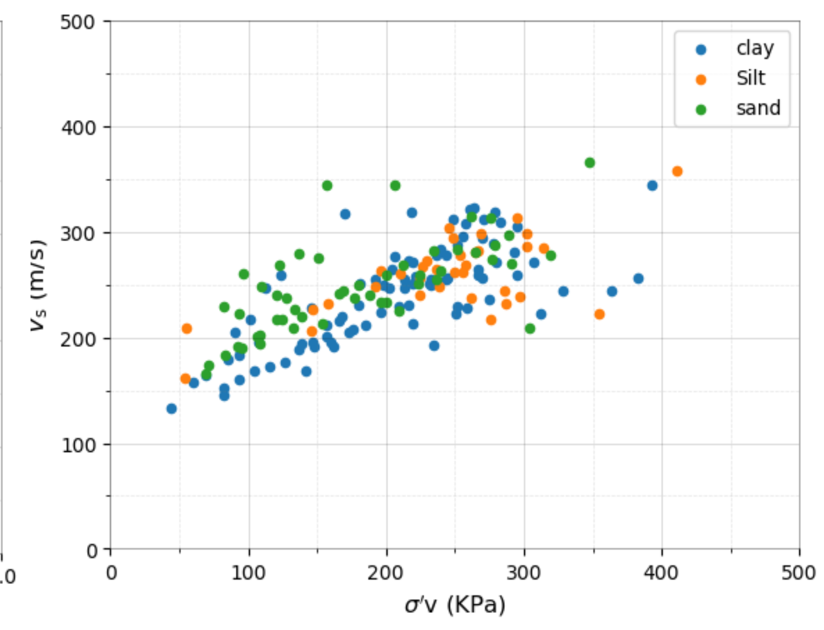
Clay, Silt, Sand

Gravel

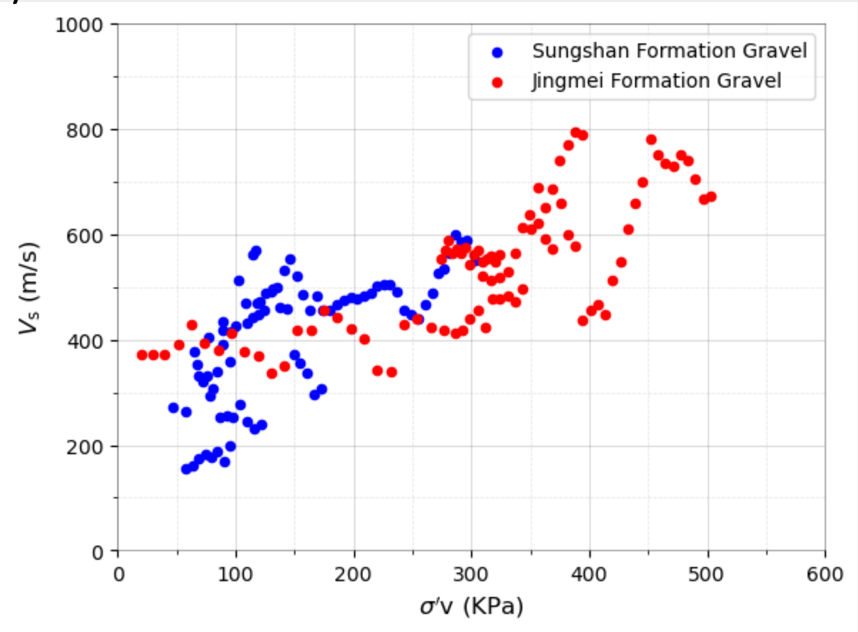
Void ratio vs. Shear wave velocity



Vertical effective stress vs. Shear wave velocity



Vertical effective stress vs. Shear wave velocity

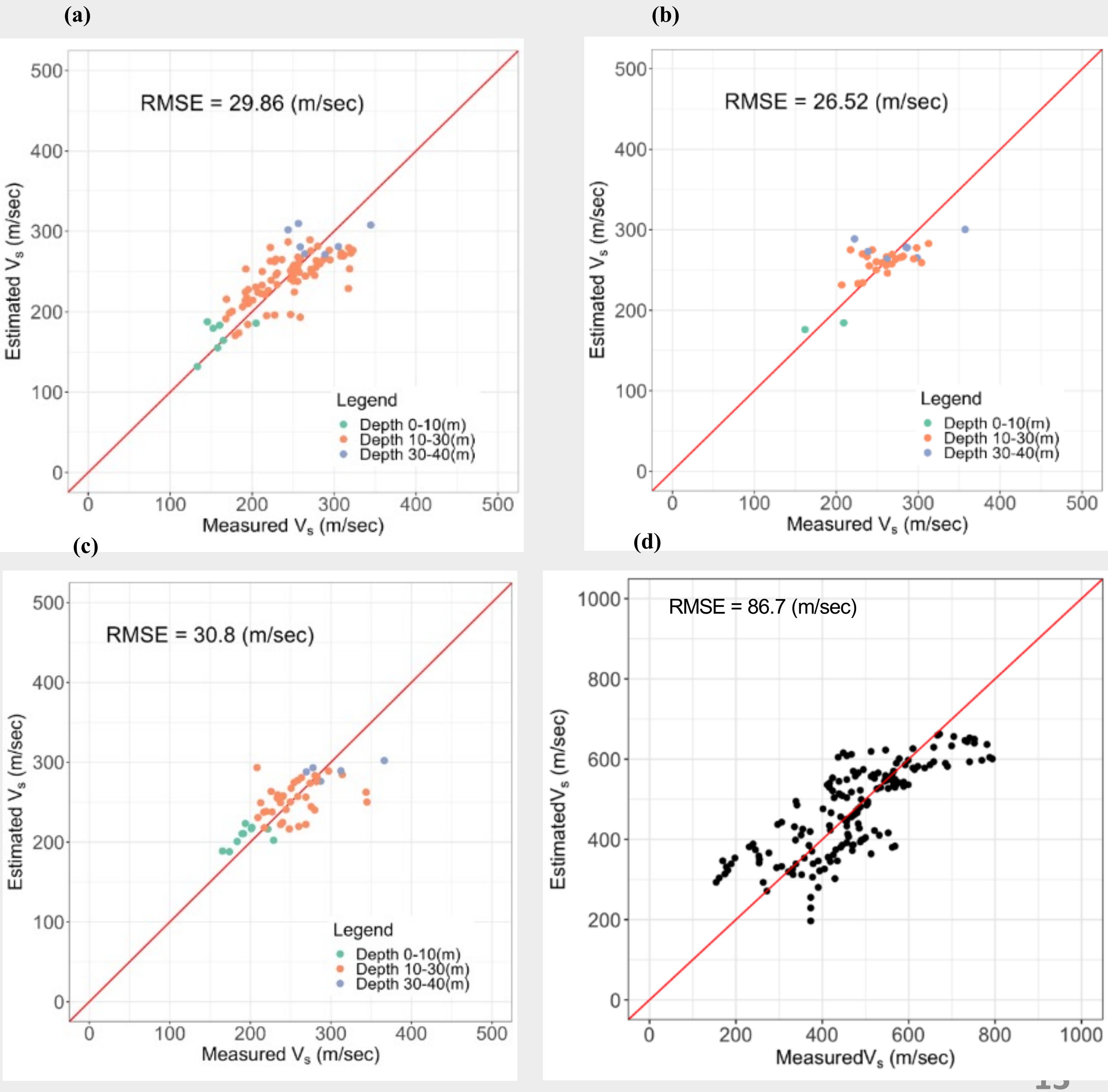


- After data filtering (velocity quality, depth condition), total of 173 samples for sand, silt and clay (51, 34, and 88 data points, respectively).
- 171 gravel samples, with 83 data pairs belonging to the Sungshan formation and 88 data pairs belonging to the Jingmei Formation.

Shear-wave velocity transformation functions

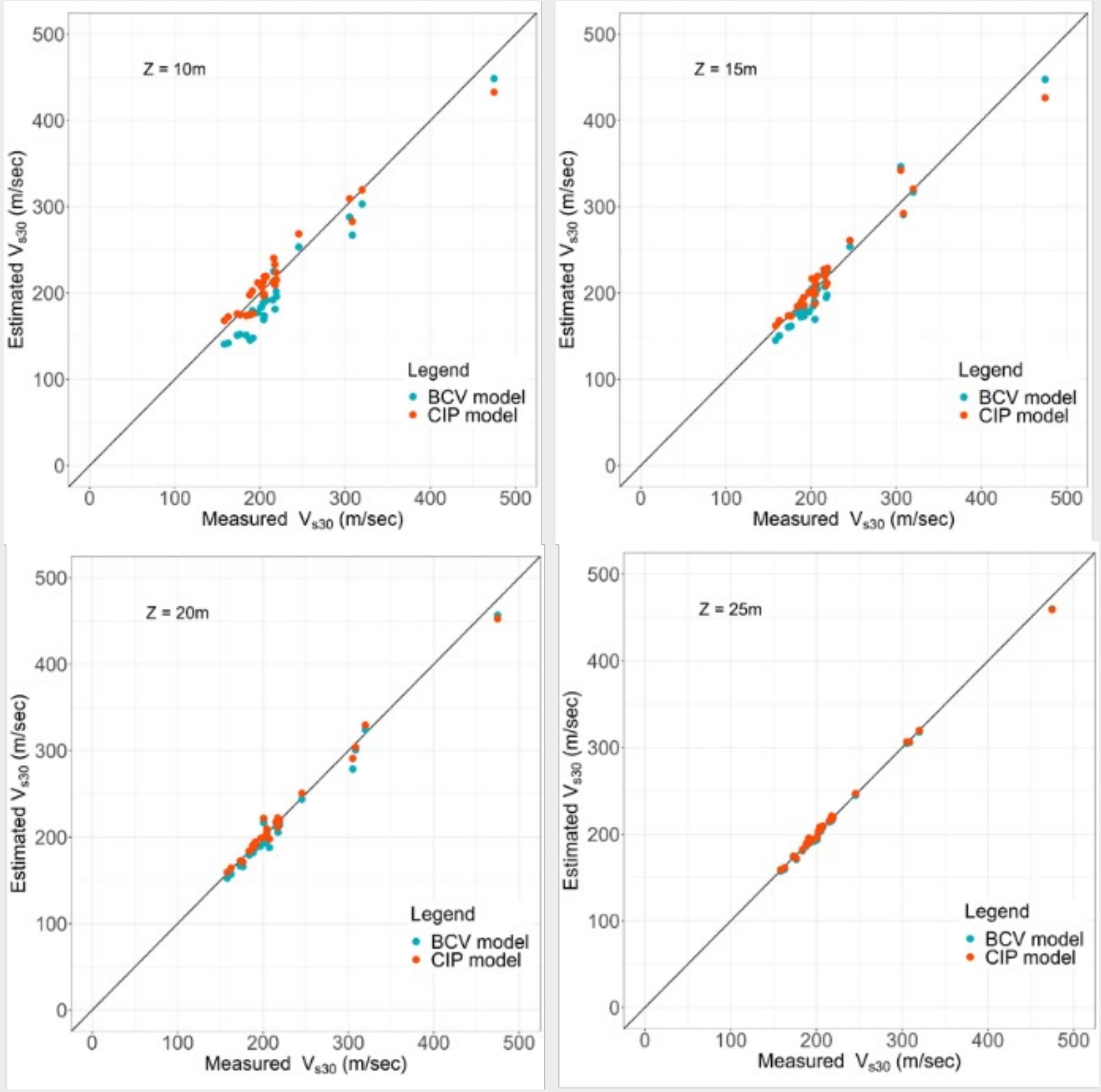
Soil type	Transformation Function	RMSE (m/s)	R^2
Gravel	$V_s = (360.6)(\frac{\sigma_v'}{100})^{0.38}$	86.70	0.60
Sand	$V_s = (240.5 - 35.9e)(\frac{\sigma_v'}{100})^{0.28}$	30.80	0.44
Silt	$V_s = (230.2 - 21.1e)(\frac{\sigma_v'}{100})^{0.23}$	26.52	0.46
Clay	$V_s = (213.1 - 21.3e)(\frac{\sigma_v'}{100})^{0.33}$	29.86	0.60

Improved RMSE compared with previous studies



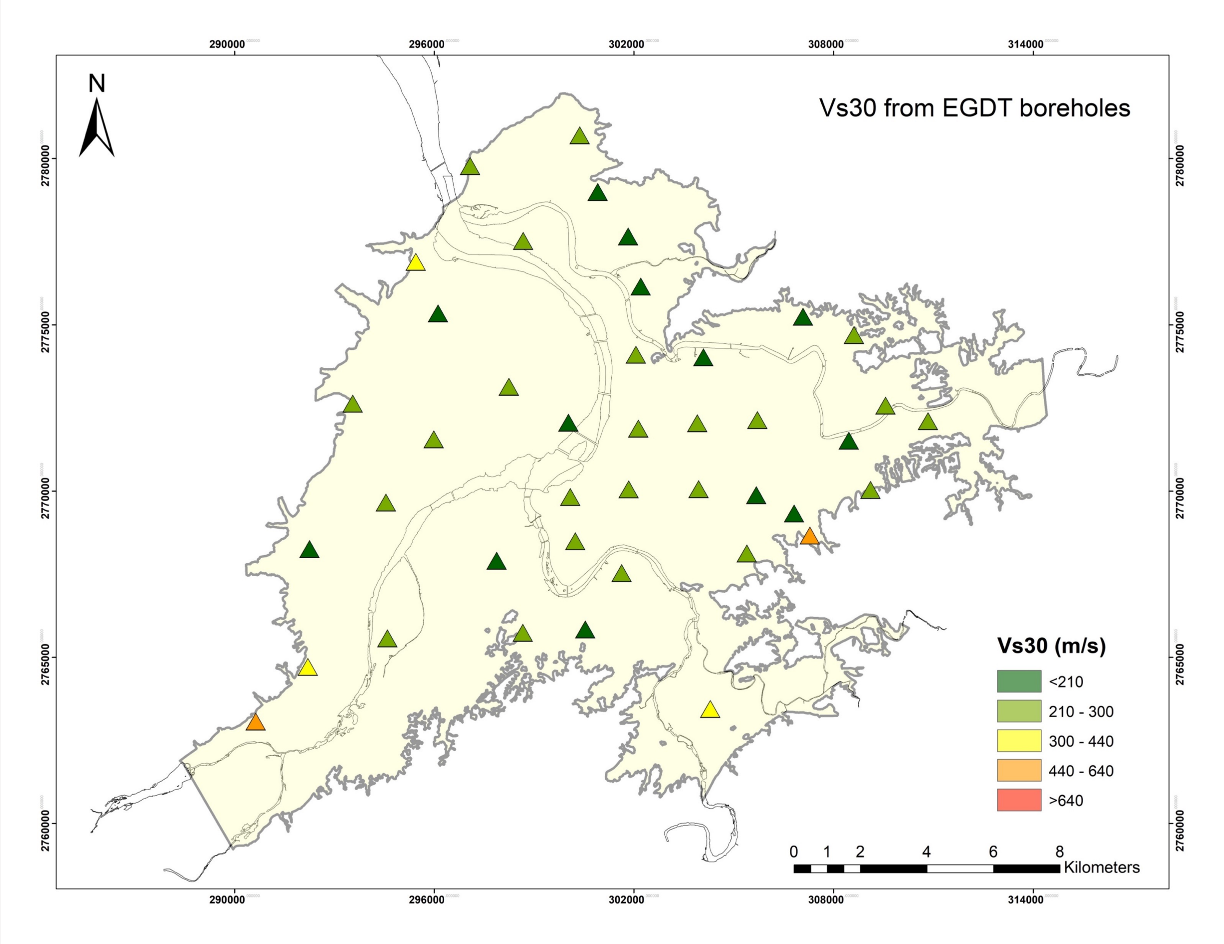
(a) clay, (b) silt, (c) sand, (d) gravel

Shallow Borehole Extrapolation

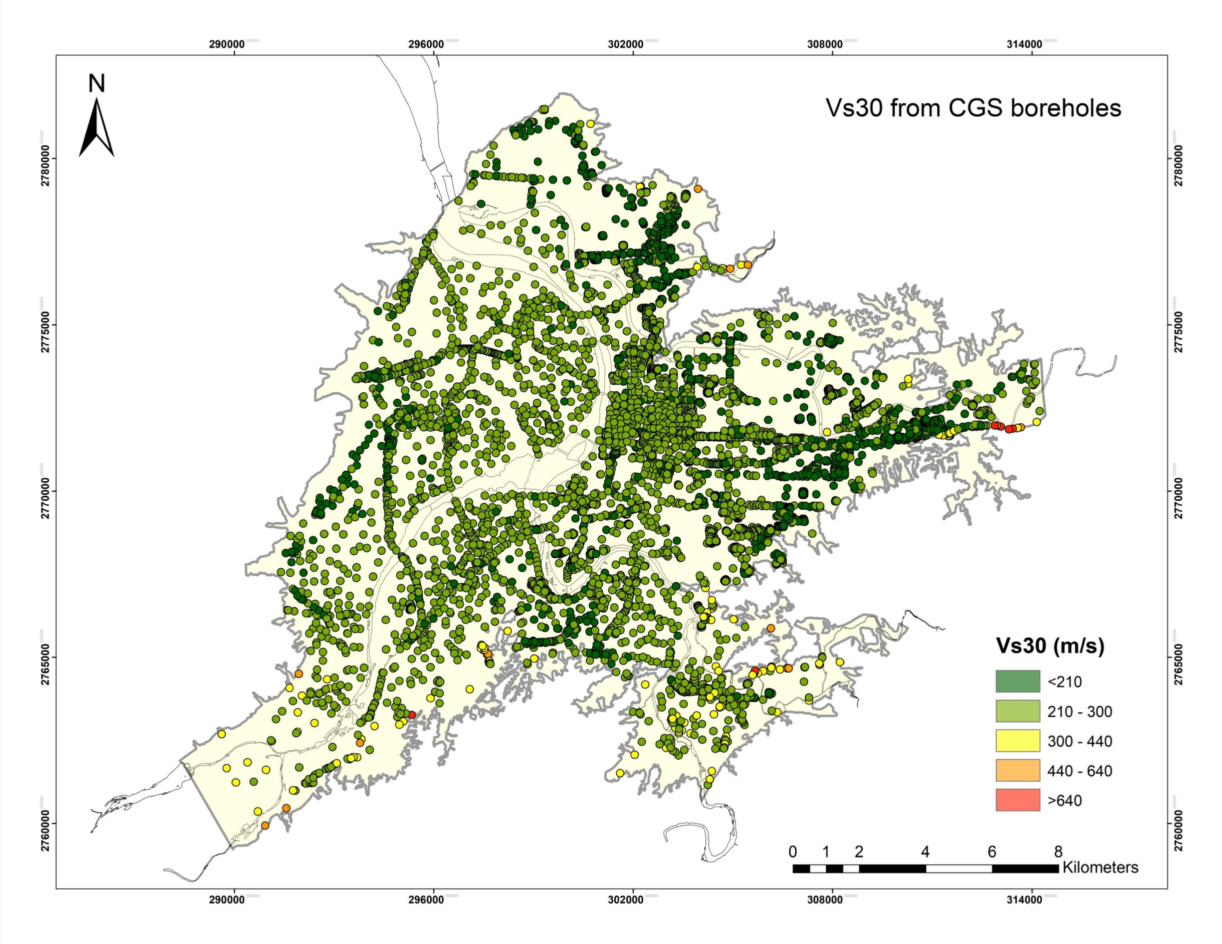


V_{S30}

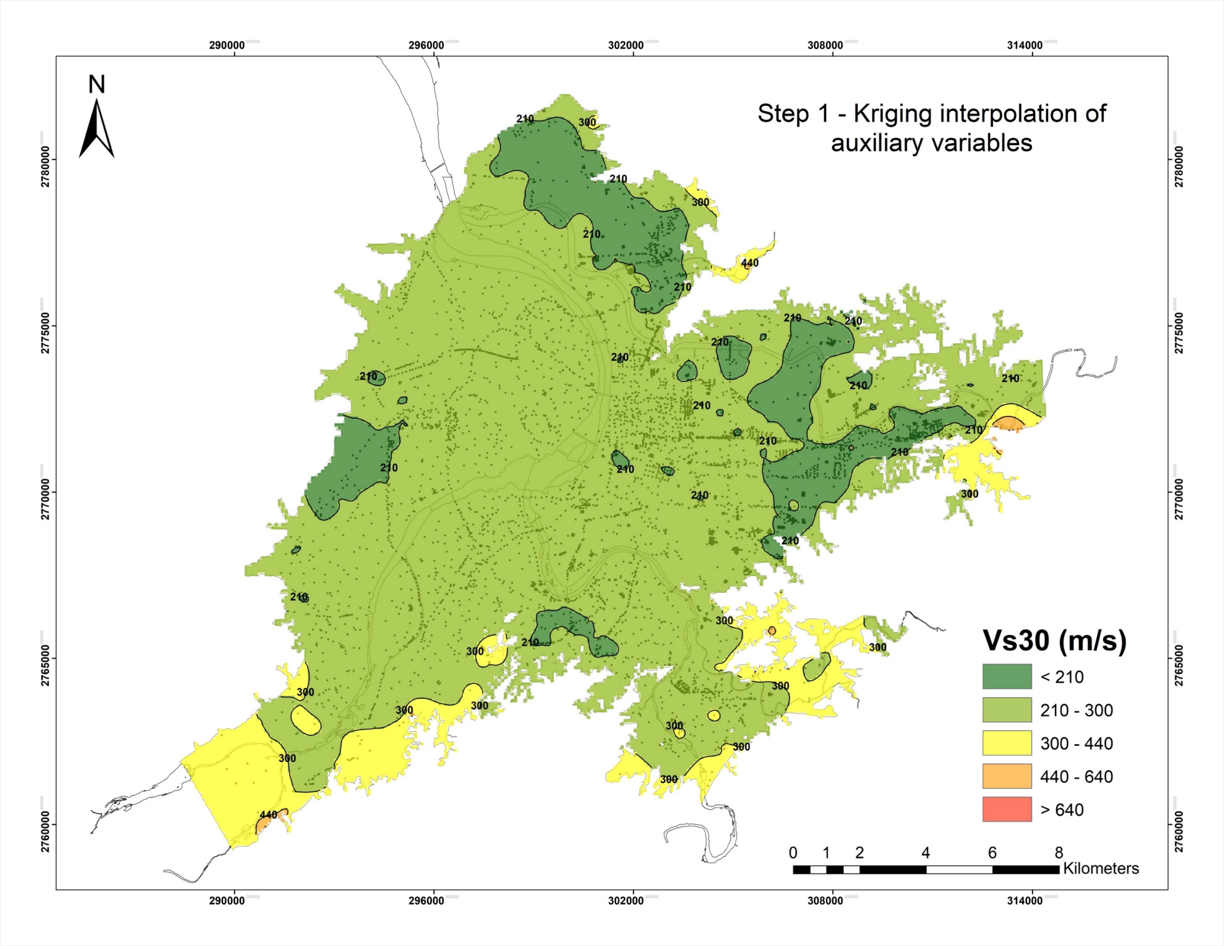
V_{S30} from EGDT boreholes – primary variable

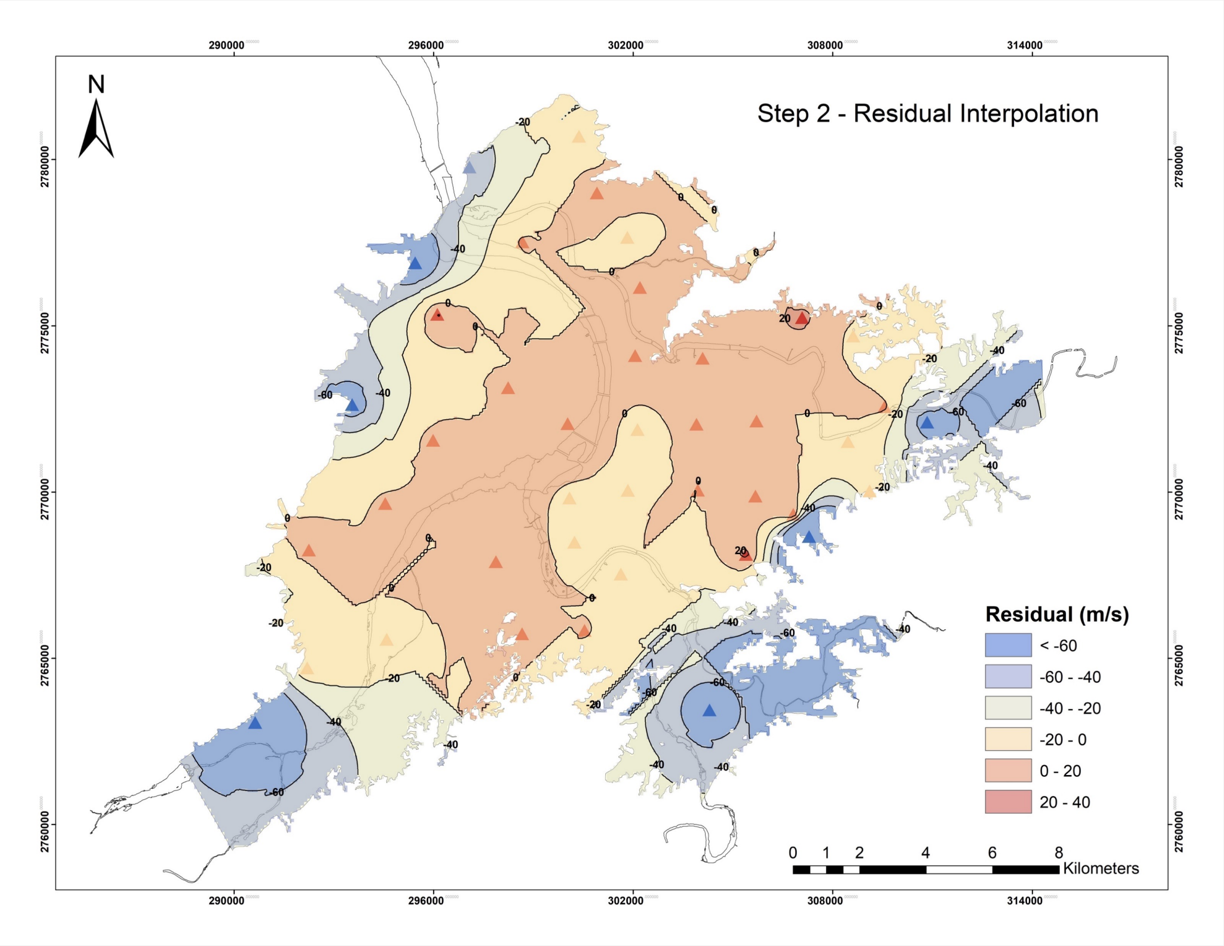


V_{S30} from CGS boreholes – auxiliary variable



Kriging with varying local means





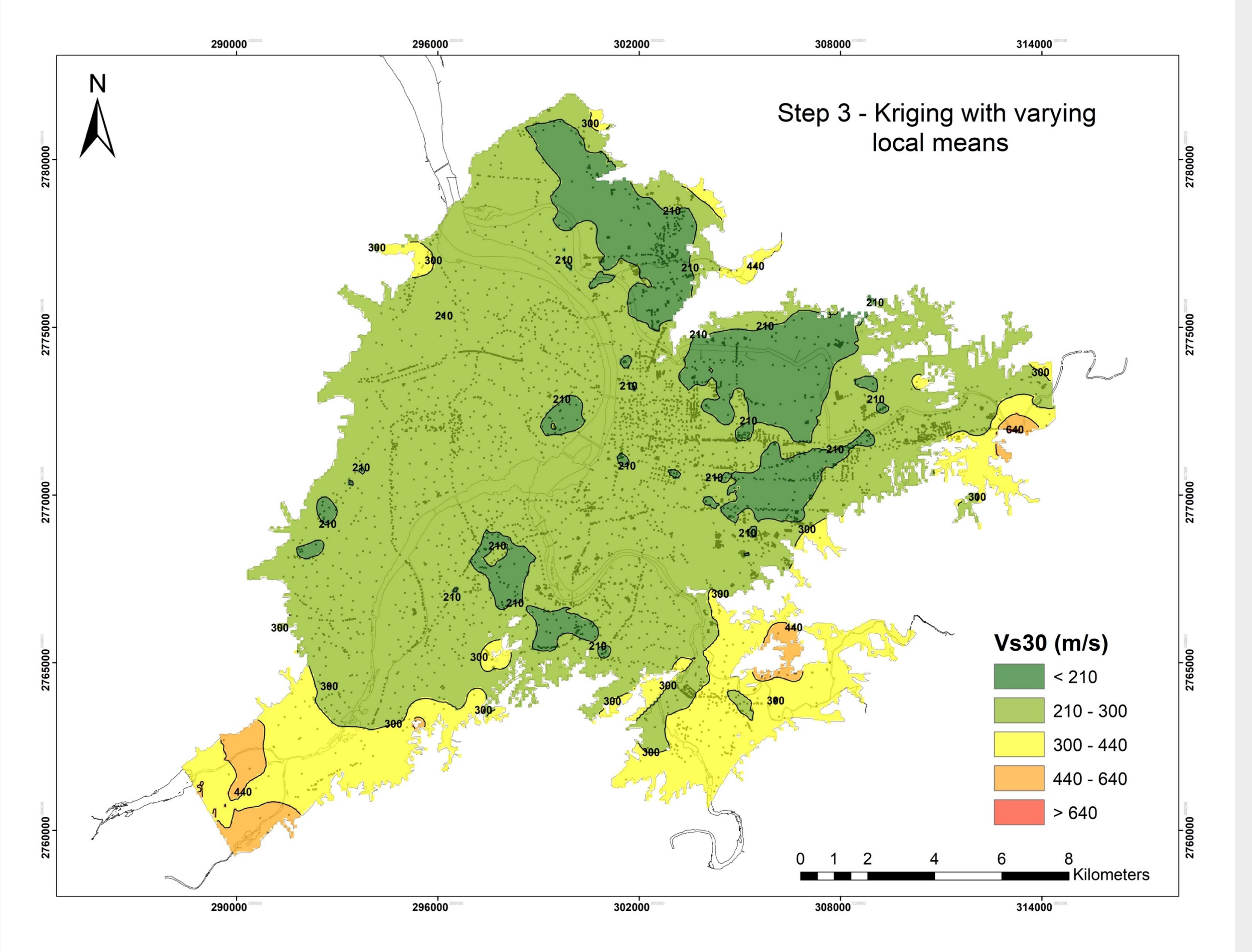
Kriging with varying local means

This study identifies three distinct regions characterized by relatively low V_{S30} values, specifically measuring less than 210 m/s:

1. North Area: The northern part of the Taipei Basin exhibits consistently lower V_{S30} values compared to other areas within the basin.

2. Northeast Area: The north-eastern section of the basin also demonstrates relatively low V_{S30} values.

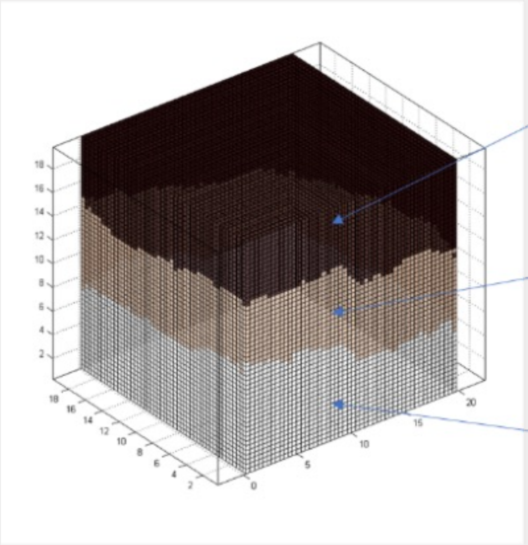
3. Small Area in the South: A small region situated in the southern part of the Taipei Basin displays low V_{S30} values.



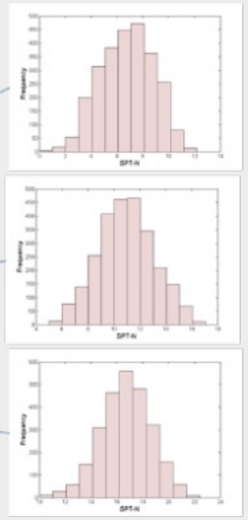
Conclusion

- Transformation functions were proposed for estimating Vs in different soil types: gravel, sand, silt, and clay. These functions improved the accuracy of V_S estimation for engineering boreholes in the Taipei Basin.
- The CIP model yielded better V_{S30} estimates for boreholes less than 30 meters compared to the BCV model. Applying the CIP model in the extrapolation process for CGS boreholes improves the number of boreholes for spatial interpolation of V_{S30} in the Taipei Basin.
- The central area of the Taipei Basin has a consistent V_{S30} range of 210 to 300 m/s. However, other areas such as in the North, Northeast and two small areas in the South of the Taipei Basin have V_{S30} values equal to or less than 210 m/s. Furthermore, the margin areas in the Southeast, East, and Southwest have V_{S30} values equal to or larger than 300 m/s.
- The use of Kriging with varying local means provided an improved representation of local V_{S30} values throughout the Taipei Basin. This can have a significant influence on the V_{S30} site classification and therefore seismic hazard assessments.

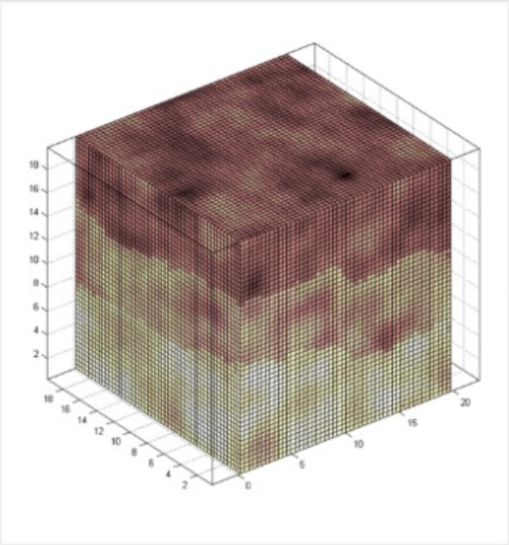
Future Work



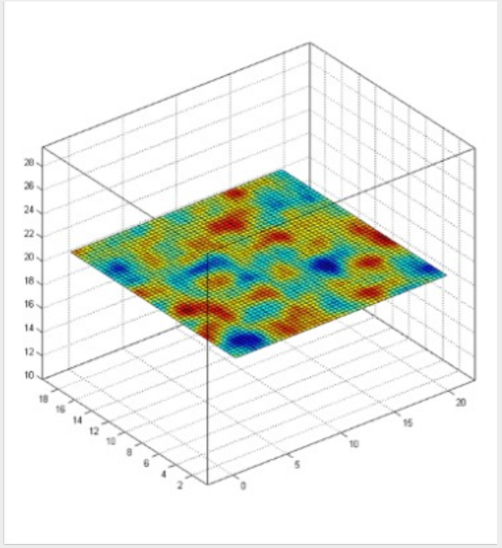
3D stratigraphy model



Soil properties

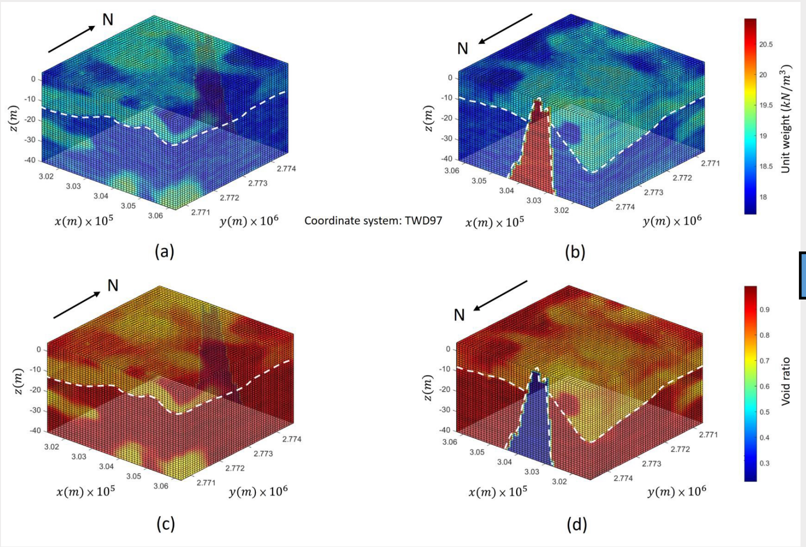


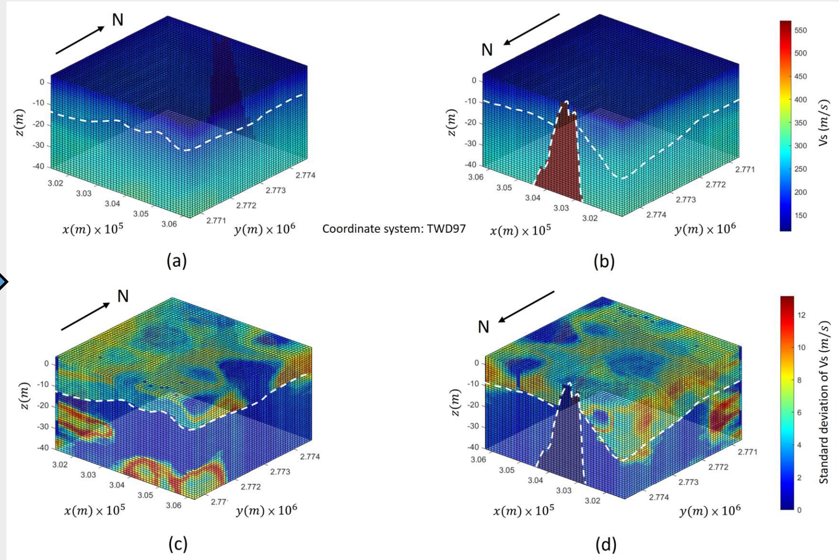
A hybrid geological and geotechnical model



Vs30, liquefaction potential, or groundwater table map

(a) (b) Average unit weight models of Zone A from different perspectives. (c) (d) Average porosity models of Zone A from different perspectives (all results from 1000 simulations).





(a) (b) Average shear wave velocity models of Zone A from different perspectives. (c) (d) Standard deviation shear wave velocity models of Zone A from different perspectives (all results from 1000 simulations).

Thanks for listening!