Towards Sustainable, Resilient and Adaptive Urban Underground Space (UUS) Exploration, Land Subsidence and Economic Impact Spatial Model (USEM) in Shanghai, P.R. China: Systematic Reviews, Model Framework, Initial Results and Pre-Determined Challenges

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Abstract. As a coastal megacity, Shanghai despite having one of the world’s leading UUS exploration for utilities, transportation, metro system, commercial and residential spaces is continuously vulnerable to serious geo-environmental hazards risks and climate change impact: land subsidence, flooding, storm surge, and seawater level rise. Hence, it is imperative to study the continuous impact of rapid UUS development, land subsidence mechanisms, related geo-environmental hazards and its socio-economic impacts towards establishing a resilient, adaptive and sustainable UUS development via spatial planning and development model to lessen future adverse consequences. The aim of this paper is to present current progressive findings of the entitled research work. Methods conducted include systematic reviews of existing online journals available at open-sourced databases such as Google Scholar and Research Gate, determined USEM’s concrete steps consists of cause-effect, spatiotemporal, scenarios modelling and comparative analysis. The data gathered are mostly secondary. The four major findings are: (1) systematic reviews summarised outcomes; (2) determined USEM model framework; (3) Initial results produced from the USEM’s first step of cause-effect analysis in Shanghai and (4) Pre-determined challenges for the model. The model’s methods are expected to be used to study Shanghai condition in comparison with developing coastal megacity like Jakarta, Indonesia. It can also be referred by related interested experts especially towards assisting deeper understanding on geo-dynamics of land subsidence, UUS and economic impact via spatial modelling and formulating policies of adaptation and resilience in developed and developing coastal megacities in the world.

1. Introduction

For many large coastal megacities such as Shanghai, Tokyo, Jakarta, Ho Chi Minh City, Bangkok and Dhaka, severe land subsidence is mainly caused by over extraction of groundwater, rapid urbanisation, soil consolidation, underground movement and flooding prone due to sea level rise and storm [1]. As rapid development demand in Shanghai is occurring faster than ever, development of UUS is targeted to become ‘big, deep, long, fast, and dense’ [2]. This has caused land subsidence to deteriorate again starting in 2000s onwards due to underground tunnel settlement and leakage, even though the net
groundwater withdrawal volume (NWV) of groundwater extraction have been controlled since 1960s [3]. Based on past records from 1920s-2000s, there were uncertainties of ‘decreased-controlled-increased’ pattern of land subsidence rate in the megacity Shanghai. In practice, UUS has been explored, developed and utilised for many important purposes in Shanghai: pipeline and power utilities, transportation tunnels: metro railway system, shopping complexes, residential, deep excavation of stormwater management and surface foundation pit excavation for high-rise buildings which are usually constructed in multi-aquifer and multi-aquitard layers.

It is continuously challenging for UUS exploration especially in coastal megacity like Shanghai due to its natural geological condition of soft soil and foundation pit seepage [2]. Shanghai despite having one of the world’s leading UUS development such as underground metro system is continuously vulnerable to geo-environmental hazards risks such as land subsidence, storm surge, and seawater level, accelerated by rapid urbanisation and climate change [4]. As the socio-economic impact of UUS exploration to land, infrastructures, properties and underground damages are long term and irreversible, it is important to have a proper feasibility impact modelling and analysis to ensure its resilience and sustainability [5]. Hence, it is imperative to study its continuous land subsidence control mechanisms and socio-economic impacts by modelling or simulation to avoid further adverse consequences especially in terms of subsidence information for disaster prevention, urban spatial planning and simulation at macro megacity scale and hydrological modelling [6]. This paper presents the current progressive systematic reviews towards the possible establishment of the USEM framework based on the integration and improvements of existing UUS-subsidence-economic impact chain, models’ framework, initial results and pre-determined challenges using Shanghai, P.R China’s case for future use. Shanghai’s land subsidence monitoring stations and correlation of tunnel settlement to land subsidence are shown in following figure 1.

![Figure 1](image)

**Figure 1.** (A). Shanghai’s land subsidence monitoring stations [7]; (B) Correlation of tunnel settlement to land subsidence in three periods of 1995-2010 in Shanghai [8].

2. **Research Methodology**

A series of extensive systematic reviews have been conducted on more than hundred existing prominent related scientific journal articles available on online database platforms such as Google Scholar and ResearchGate. The literatures consist of researches conducted from period of 1960s-2000s and are gathered using key search terms: ‘UUS’, ‘land subsidence’, ‘economic impact’, ‘spatial modelling’ and ‘Shanghai’. The research scientific journals are systematically reviewed by their publication year and related content. Gaps-to-be-filled are determined based on previous similar researches, theories, models, methods and arguments to reach research novelty and producing the so-
called ‘USEM model’ in this multidisciplinary research. After the steps in USEM framework are determined, the first step: cause-effect analysis is initially conducted. The cause-effect analysis tries to study the relation of determined causing factors: land subsidence risks intensity, hazards assessment, urbanisation rate, UUS exploration, long-term drawdown of groundwater and available adaptation policies with the economic impact factors: land, underground, infrastructure, buildings and socio-economic.

3. Research Findings and Discussions
There are basically four main progressive findings for this on-going research which are (1) determined gaps towards establishing integrated model framework called USEM; (2) Detailed USEM steps and framework; (3) Preliminary cause-effect execution of the model using Shanghai and lastly, (4) Pre-determined challenges and improvements of the model.

3.1. Research Gaps towards USEM Framework
Based on the extensive systematic reviews, there are four type of gaps determined towards supporting the realization of the USEM framework namely research, theoretical, method and argumentative gaps. The determined gaps are summarised in table 1.

| Type of Gaps          | Gaps potential to be filled in for Shanghai context                                                                 |
|----------------------|-------------------------------------------------------------------------------------------------------------|
| Researches           | Land subsidence risks, UUS-subsidence-economic impact spatial modelling at megacity scale                     |
| Theoretical          | Integrated-combined theory of factors, cause-effects, suburban regions, UUS-economic externalities uncertainties |
| Models and methods   | Major models and methods integration for more accurate data analysis – cost-benefit analysis – vulnerabilities-marginal damage – complex multifaceted analysis – optimal policies to mitigation social welfare losses |
| Argumentative        | Necessity for comprehensive evaluation of UUS multiple potential resources involving spatial and land allocation, building-underground subsidence – interdependence land use and human activity - socioeconomic system modelling – Fuzzy Analytical Hierarchy Process (FAHP) – limitations in current subsidence prevention zones in Shanghai |

Hence, based on the summarised gaps, the importance of having an adaptive, resilient UUS-subsidence-economic spatial modelling or USEM is crucial and potential to be filled as new added knowledge in the current related body of literatures. There are many models and analysis in hydrodynamic-economic-spatial relations however, they are unique in their own terms of context, disintegrated, merely check list assessment-based, do not focus specifically on the UUS exploration, development and additionally, spatial modelling for example, hydrodynamic model structure for property values [9]; land price-subsidence-spatial [10]; UUS-hazard risks [11]; FAHP for infrastructures [12]; property-metro-subsidence [13]; housing price-subsidence-spatial [14] and subsidence-economic impact assessment framework [15]. It was also observed that the existing land subsidence prevention zone in government management guidelines does not sufficiently consider the vulnerability of significant infrastructures in Shanghai [14]. Issues such as data lacking; longer time series data of land use; need for production of more reliable simulated results; suggestions for more accurate and comprehensive data permit for more accurate results; introduction of hydrodynamic model into inundation simulation and analysis; more detailed socio-economic impacts; loss evaluation and cost-benefit analysis warranted to identify localities that are particularly vulnerable [16] are among of the common issues identified in the literatures suggested for future potential research.
3.2. **USEM steps and framework**

Hence, based on the determined gaps, following steps are specifically designed in the USEM framework to further achieve the research goal and purposes. USEM consist of four major steps, explanation and equation as shown in table 2.

| Steps                                      | Explanation                                                                                                                                                                                                 |
|--------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| **1. Cause-effect:** Causing or critical determinant factors | Land subsidence hazards risks assessment, goaf subsidence, surface water system, fault and ground fissures, karst subsidence, sand liquefaction, aquifer characteristics and pumping locations, subsidence (refer equation 1), probability flood zone designation and UUS exploration, determine suitability classes for development |
| Economic impact factors                    | Land, underground, infrastructure, buildings and socio-economic (multiple regression of cause and effect factors)                                                                                           |
| **2. Spatiotemporal relationships**        | Fitting of variables, fluctuation of economic impact factors, possible loss caused by the UUS exploration, intangible positive effect factor, digital elevation and inundation modelling, land use and land cover change, land use simulation, subsidence-economic system modelling, interdependence of land use and human activity changes in coastal areas (see equation 2) |
| **3. Case scenarios modelling**            | Three type scenarios establishment: *Business as Usual, BaU; Countermeasures, CM; and Worst-case scenario (deteriorate).*                                                                                 |
| Minor comparative                          | Inductive and context dependent, policy implications. Using secondary data to compare situation of Shanghai with other developing coastal Southeast Asian megacity, pre-determined as Jakarta, Indonesia with land subsidence issue categorised as ‘underway’ by International Geoscience Programme (IGCP) by United Nations Educational, Scientific and Cultural Organisation (UNESCO). |

\[
Sub_i = \rho g \text{draw}_{ij} b_i \alpha
\]  

(1)

Where \( \rho \) is fluid density (kg/m³), \( g \) is acceleration due to gravity (m/s²), \( b_i \) is the original thickness of the confining unit (m) and \( \alpha \) is the compressibility of the confining unit material (m·s²/kg). The thickness of the confining unit varies across model cells.

\[
\text{Disaster Risk} = \text{Hazard} \otimes \text{Exposure} \otimes \text{Vulnerability or Capacity}
\]  

(2)

Where \( \otimes \) represents the overlay analysis in geographic information system (GIS) whereby, this equation is used to express the definition of disaster risk as the sum of hazards (causing factors) overlayed spatially with exposure and vulnerabilities or capacity such as economic impact [17].

3.3. **Initial cause-effect results for Shanghai**

The preliminary findings indicate: There was negative correlations between cumulative subsidence and UUS development in Shanghai. As cumulative subsidence decreases (*increment in rate*), UUS development increases. It is important to predict future situations in years 2010 and onwards based on the previous record of uncertainties from rapid development-stabilised and accelerate again in 1990. Following figure 2 and table 3 visualises the initial correlation between cumulative subsidence and UUS development from 1920-2010 in Shanghai.
Figure 2. Shanghai’s cumulative subsidence by year to UUS development from 1920-2010.

Table 3. Correlation between subsidence and UUS development in Shanghai.

| Year | Cumulative subsidence (mm) | UUS development (10^6 sqm) | Development Phase     |
|------|----------------------------|----------------------------|-----------------------|
| 1920 | 0                          | 0.3                        |                       |
| 1930 | -100                       | 0.3                        |                       |
| 1940 | -300                       | 0.3                        | I - Rapid development |
| 1950 | -500                       | 1.9                        |                       |
| 1960 | -1300                      | 1.9                        |                       |
| 1970 | -1600                      | 1.9                        | II - Stabilised       |
| 1980 | -1700                      | 1.9                        |                       |
| 1990 | -1750                      | 7.3                        |                       |
| 2000 | -1900                      | 15                         | III - Accelerated     |
| 2010 | -2000                      | 9                          |                       |

Furthermore, proper continuous maintenance and improvement measures in the central business district (CBD) of Shanghai are needed for UUS development especially in high prone and risky areas, as well as to maintain high land price. New development areas at Northern and Southern Shanghai need to have controlled subsidence rate to produce future less risk with higher economic prices. Following figure 3 and table 4 visualises the results of correlation between UUS area, real estate price and cumulative subsidence.
Figure 3. Spatial correlation between UUS area, real estate price and cumulative subsidence in Shanghai by 2010.

Table 4. Correlation between UUS area, real estate price and cumulative subsidence of Shanghai in 2010

| District                          | Cumulative subsidence (mm) | UUS development area (10^4sqm) | Real estate price (RMB/m²) |
|----------------------------------|-----------------------------|--------------------------------|-----------------------------|
| Pudong                           | 1000                        | 854                            | 10,031                      |
| Urban centre (Huangpu, Hongkou, Yangpu) | 1000-2000                  | 634                            | 40,358                      |
| Minhang                          | 600                         | 487                            | 7,670                       |
| Baoshan                          | 200-600                     | 209                            | 6,955                       |
| Jiading                          | 200-600                     | 79                             | 5,928                       |
| Jinshan                          | 200-600                     | 42                             | 3,847                       |
| Songjiang                        | 200                         | 127                            | 5,793                       |
| Qingpu                           | 200                         | 82                             | 5,547                       |
| Fengxian                         | 200-600                     | 46                             | 4,853                       |
| Chongmin                         | 200-400                     | 18                             | 4,721                       |

From figure and table, it can be observed that highest cumulative subsidence 1000-2000 mm is at urban centre (Huangpu, Hongkou and Yangpu district), while its UUS development area is 634 $10^4$sqm. Nevertheless, it still has the highest real estate price at 40,358 RMB per m². Meanwhile, the lowest cumulative subsidence is in Songjiang and Qingpu at 200 mm with 127 and 82 $10^4$sqm of UUS development area respectively, nevertheless, their real estate price is quite reasonable for 5,793 and 5,547 RMB per m², respectively. This shows that UUS development and land subsidence do not negatively impact real estate price whereby unexpectedly, the area with highest subsidence risk could
possess such high real estate price and those with the lowest cumulative subsidence do not significantly own the highest real estate price. The complex relationship still needs further justification especially on the theory of real estate prices determinants factors etc. Regardless, it is expected that without proper spatial planning, greater risks of uncontrolled UUS development can cause adverse feasibility impact in future especially in terms of inundation and other economic impact such as land, buildings, infrastructures and underground structures. As land, infrastructures, buildings, properties and underground structures demand may continue to rise by 2050, further improvisation and proper control of adaptation and resilient policies especially involving the UUS development, land subsidence, its monetary impact via sustainable spatial planning is especially important.

3.4. Pre-determined Challenges for USEM framework

Current deficiencies of the USEM model are its complexity of assessments-spatial data framework. It is determined that the model integration will produce a complex multifaceted UUS-subsidence-economic spatial model. However, if it is not too ambitious, it should have its limits. To execute such complex model with various methods, equations and analysis will requires expertise in data gathering and GIS simulation. Hence, some data are produced based on assumptions. Nevertheless, the so-called USEM framework is indeed significant towards enabling and serving interested experts in field of urban planning and civil geotechnical engineering multidisciplinary.

4. Conclusion

The USEM framework is produced as a research progress in promoting adaptive, resilient UUS exploration along with land subsidence issues in Shanghai by studying its impact to urban economics and spatial planning. The framework can be referred and improvised further to provide deeper understanding on the geo-dynamics of UUS development, land subsidence, economic impact and spatial planning model in other megacities in the world. This research tries to open for possibilities of integrating the existing models to create a future integrated comprehensive modelling for UUS-subsidence-economic spatial chain using the case of Shanghai.

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