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COMPARATIVE STUDY OF NUMERICAL SIMULATION OF COASTAL FLOODING IN URBAN & ESTUARINE AREAS

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Abstract: Two different approaches for numerical simulation of coastal flooding in urban & estuarine area have been carried out within the framework of a bilateral research project supported by the National Science Fund of Bulgaria and the Ministry of Science & Technologies of the PR of China.

A high resolution digital elevation model has been established for the Asparuhovo - Karantina area in Varna, Bulgaria, located at Black Sea coast. The area is considered with high risk of flooding, being at low elevation above the sea-level, with the presence of a small river (gulley) in the neighborhood. A MIKE FLOOD approach was used by Bulgarian team to simulate inundations in the considered area under example scenarios with expertly formulated data for compound flooding: coastal flood (storm surge) in combination with pluvial/flash flood (heavy rainfall in the urban area), and river overflow due to excessive rainfall over an extended period.

Concurrently a SWASH model has been elaborated by the Chinese team to study coastal flooding for the same geographical area, for the same scenarios for water levels and wind-wave climate conditions. Simulation results of wave transformation in coastal area obtained by SWASH model indicate that, the shoaling effect near shore and wave run-up and breaking in the swash zone may aggravate the flooding disaster on the beach, especially when a severe storm generate intense water level rise.

Key words: Digital elevation model, field measurement data, numerical modeling

INTRODUCTION (Background and Objective of the Study)

Since centuries, protection of coastal communities against floods was one of the key stones for the development of human civilizations. Today, this is still a key issue for the entire world. The urban population of the world has grown rapidly from 746 million in 1950 to 3.9 billion in 2014, expected to surpass six billion by 2045 - a sizeable challenge for urban water management. Climate change impacts affect cities significantly — increased flood risks, increased frequency/severity of extreme events (floods, droughts, storms, heat waves, etc.). The increase in extreme weather events and flooding in particular has serious potential consequences for human health, livelihoods and assets.

Flooding in coastal urban areas (urban flooding) can be caused by high intensity rainfall, or storm surge floods, or river floods, or wave action in coastal zone, or the most dangerous combination of these events, whereby the city sewage system and draining canals do not have the necessary capacity to drain away the amounts of water that are falling. Typical examples of urban flooding were catastrophic flash floods in Bulgarian cities of Varna/Asparuhovo and Dobrich, in June 2014, with casualties' loss of human life, and huge damage of infrastructure and properties. This requires the study of hydrodynamic processes in very complex terrain conditions (coastal zone with urban infrastructure). "Composite modelling" or "Hybrid modelling" is one approach widely used over the past few decades to achieve a reliable forecast of inundation in floodplain areas at different scenarios. The "Composite Modelling" integrates physical modelling, numerical simulations, and verification with field measurement data. This present-date research approach can combine the main strengths of prototype data, physical and numerical modeling and this way to improve modeling and design. These elements of composite modeling can essentially complement each other – physical model provides verification data for numerical models; model simulations provide the continuum information to bridge the gaps in field data, etc. Thus increasing quality of the study results at the same cost or obtaining the same quality at reduced cost and/or reducing uncertainty at the same cost, since uncertainty reduction is also quality issue. Following the principles of composite modelling, physical and numerical modelling can improve further and broaden their range of applicability, [1].

The objective of the present study is to test and discuss two different approaches and techniques for numerical simulation (as element of composite modeling) of coastal flooding in urban and estuarine area. It should be pointed out that the greatest advantages of numerical modelling are its low cost compared with physical model tests, different options that it offers, possibility to repeat many times the simulation, lack of scale effects and of course extraction of data of all kinds by "virtual" probes without interfere with the flow. In any case the numerical model needs to be calibrated using sufficient reliable field data, [2].

The paper contains brief description of used numerical tools (MIKE21/MIKE FLOOD, and SWASH) and presents some example results obtained during numerical simulations of flood in the selected coastal area.

CASE STUDY AREA (MODELED AREA)

The two numerical approaches for simulation of coastal flooding have been tested for the conditions of an urbanized coastal area Asparuhovo - Karantina near Varna, Bulgaria, (Fig. 1). It is located in the southern part of Varna Bay on the western coast of the Black Sea (a closed sea, with negligible tidal variations).

Figure 1. Case Study Area near Varna, Bulgaria

This is a residential area that includes a sandy beach and a small river (gulley) in the southeast part of the beach. The residential area behind the beach is considered with high risk of flooding, being at low elevation above the sea-level. The numerical model also includes the fishing harbor to be built in the area.

MODELS AND RESULTS

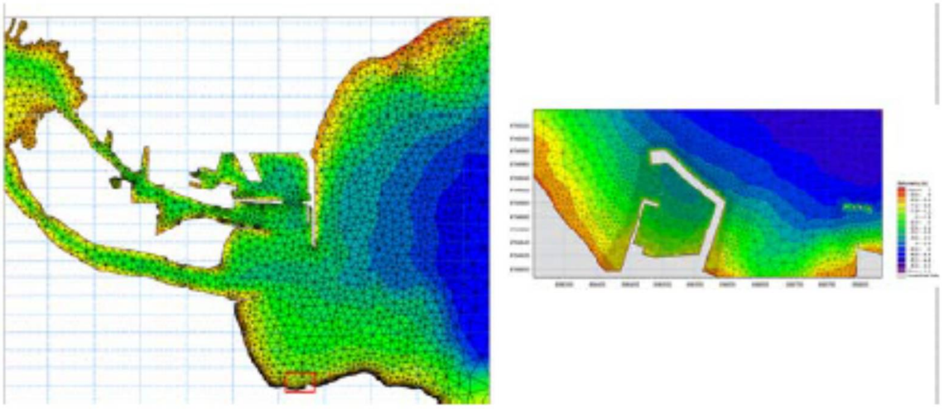
MIKE 21 approach

MIKE 21 was developed by DHI (Danish Hydraulic Institute) and designed for 2D free surface modelling of flow and waves, sediment transport and environmental processes for estuarine and coastal applications. From wide range of models in MIKE Software family, released during more than 30 years, numerical models MIKE FLOOD, MIKE21 SW and MIKE21 BW were used in this study.

MIKE FLOOD is flexible software with the possibility to integrate 1D (MIKE 11 and/or MIKE URBAN) and 2D (MIKE 21 FM) models and perform more complex hydrodynamic simulations by different combinations between the 1D and 2D model.

MIKE 21 SW (Spectral wave) is a state-of-the-art third generation spectral wind-wave model that simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas. It includes two different formulations: A fully spectral formulation and a directional decoupled formulation. The first formulation is based on the wave action conservation equation and the second one is based on a parameterization of the wave action conservation equation. MIKE 21 SW is mainly used for simultaneous wave analysis on regional and local scale. A coarse mesh and large time steps are employed for the regional scale, while a high resolution boundary and depth-adaptive mesh is used for the shallow water areas.

Several data sets were combined in the process of the generation of the unstructured computational mesh for the simulations with MIKE 21 SW of Asparuhovo - Karantina beach area. The generated meshes are illustrated on Fig. 2 (a, b).



a) b)

Figure 2. Unstructured flexible mesh for MIKE SW simulations:
a) Varna bay; b) Asparuhovo beach area and fishing harbor Karantina

A MIKE SW model was applied to evaluate waves entering shallow water, and provide boundary conditions for a MIKE 21 BW (Boussinesq Wave) model to study wave diffraction/transformation in the nearshore zone and in the harbor area.

The numerical model simulation results from MIKE21 SW model were compared with water level (storm surge) and wave data for the shallow water and wave breaking zone of the Asparuhovo beach area provided from Institute of Oceanology-BAS.

On the basis of the numerical bathymetry and the prepared meshes for the SW model, an additional numerical model has been set up with a larger resolution for the Karantina area. In order to construct the final model for the simulations of combined flooding including spill of the river combined with rising sea level driven by a storm. The described high resolution model (DEM) in the area of the river, harbor and beach is illustrated on Fig. 3.

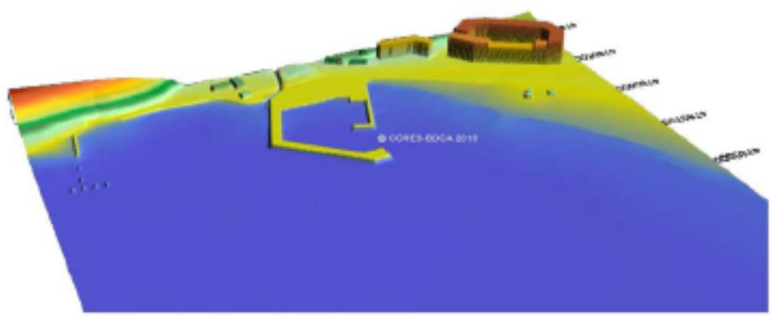


Figure 3. 3D Visualization of the Digital Elevation Model (DEM) of the Asparuhovo beach and residential area, including sea bathymetry, sand beach, roads, buildings, fishing harbor and a small river

Digital Elevation Model (DEM) of Karantina area was created with a spatial resolution of 1 x 1 m in plan, and 15 cm in vertical on the base of data from hydrographic measurements and terrain scanning integrated in a GIS environment, and used to generate a 3D surface map on the base of standard triangulation techniques.

A MIKE FLOOD model was used to study riverine flow in the small river (1D approach), followed by a 2D MIKE 21 FM model, integrating both sea level elevation (coastal flooding) and the fluvial flood (river overflow). The calculation mesh comprises of 500 000 finite elements. Bed resistance is varying in the domain, higher values close to the beach and lower values offshore.

For numerical simulation of the inundation in the case study area a gradual increase in the mean sea level was simulated to levels typical of extreme meteorological events with a very long return period, and which levels are quite significant in terms of beach flooding and overtopping the planned new harbor and coastal infrastructure.

A combination with multi-year river discharge was added to try to estimate compound flooding. Results of the simulations in the high-resolution DEM of the study area are illustrated on Figure 4.

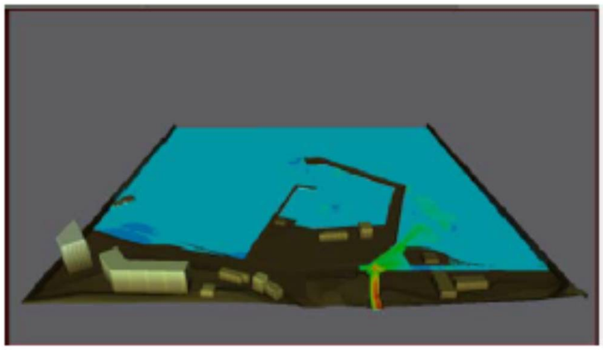


Figure 4. Example results of calibration tests by MIKE FLOOD model of compound coastal & fluvial flooding in Asparuhovo - Karantina area (Sea level rise and high water coming from the small river)

SWASH approach

SWASH is an operational public domain code for simulating wave fields, rapidly varied flows and transport phenomena in 1D, 2D or 3Ds in coastal waters. The governing equations are the nonlinear shallow water equations including non-hydrostatic pressure. SWASH provides a general basis for describing complex changes to rapidly varied flows typically found in coastal flooding and wave transformation in both surf and swash zones due to nonlinear wave–wave interactions, interaction of waves with currents, and wave breaking as well as run-up at the shoreline.

A SWASH model has been elaborated by the Chinese team to study coastal flooding for the same geographical area, for the same scenarios for water levels and wind-wave climate conditions. SWASH is referred to a non-hydrostatic wave-flow model aimed to simulate wave transformation in coastal area.

The model domain is 1500m×1000m shown in Fig. 5. A uniform grid of 1500×1000 cells (dx = dy = 1.0 m) and 1 vertical layer is employed. The northern boundary uses weakly reflective boundary condition to generate irregular waves of JONSWAP spectrum and the spectrum parameters are Hs=3.0 m, T_{mean}=8.8 s, Dir=76 deg. These parameters are calculated by a three-nested SWAN model.

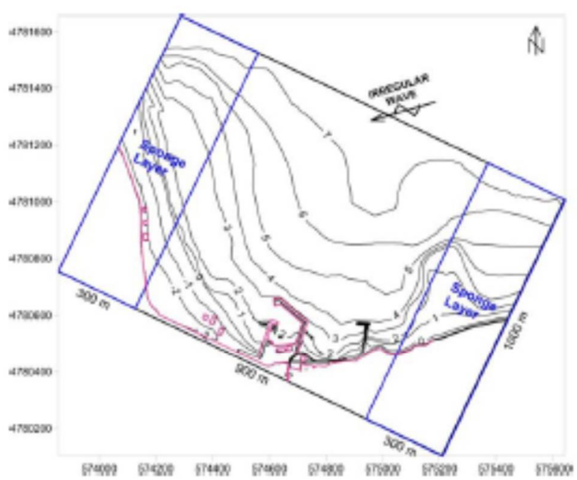


Figure 5. Schematic view of SWASH model domain

At the western and eastern boundaries, sponge layers with width of 300 m are applied to absorb short wave energy. At the southern boundary, discharge per unit width in the river upstream with a linear time-varying increase from 0 at the initial time step to 7 $m^3/s/m$ at the end of simulation is given. The still water level in the domain is set to be 0.5 m initially and rise up slowly to 1.2 m at the end of simulation to describe the large-scale storm surge set-up during extreme event. Figure 6 shows wave transformation and inland inundation scenario along the Asparuhovo - Karantina coast during the simulation period of 20 min.

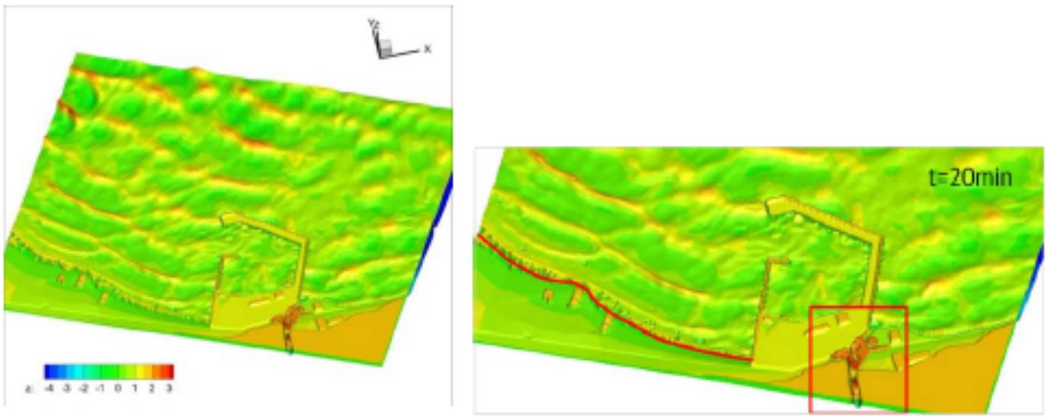


Figure 6. Detailed results after 20 min. simulation period of flooding by SWASH in Asparuhovo - Karantina coast

11 "virtual" wave gauges are set in study area, (Fig. 7), to investigate the time series properties in the Asparuhovo - Karantina coastal area. P0~P5 is located at initial still water depth of -1.2 m, 0.5 m, 1.5 m, 3.5 m, 5.0 m and 6.0 m, respectively, aiming to explore the wave transformation properties from offshore to the swash zone. E1 is located at the estuary and R1, R2 are located in the upstream river. They are used to look up the interactions between the storm run-off from inland and extreme waves from seas in the estuary area.

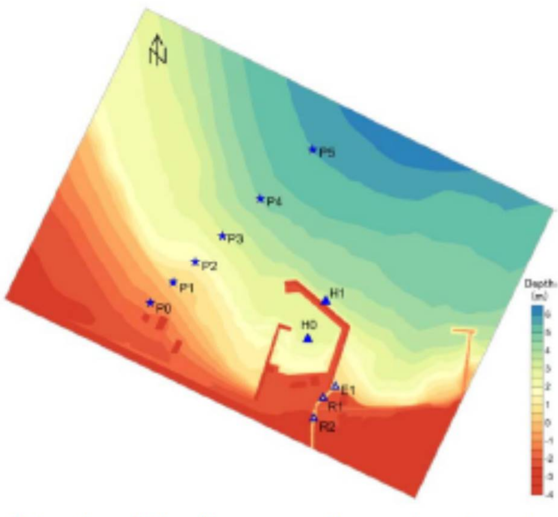


Figure 7. Locations of "virtual" wave gauges for extracting a time series results

Figure 8 shows the time series of significant wave height Hs at point P5, P2 and P0. Waves at P5 are common waves in relatively deeper waters larger than 5.0 m. With the approaching coast, the bottom friction and wave breaking effects start to play a dominant role in gradually decreasing of wave height – from 1.66 m at P5 to 0.96 m at P1. As shown from the time series at P2 the nonlinearity increases in shallow waters and shapes of wave crests become steeper and wave troughs become more flat compared the shape of deep water wave. It should be noticed that, P0 is located at the swash zone, where the breaking waves swash up-and-down with violent turbulence and rotational flows. As shown in the "gauge" P0 in Fig. 8, located at the swash zone on the beach, the wave uprush height can reach up to +1.5 m above the still water level. That means that large waves can aggravate the coastal disaster in the Asparuhovo - Karantina area and deserves prominent attentions.

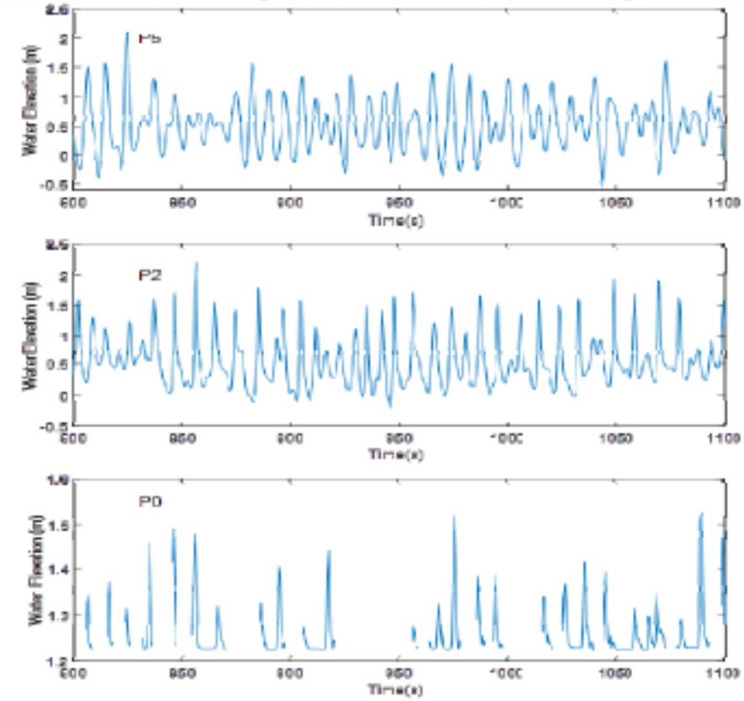


Figure 8. Time series at points P5, P2 and P0

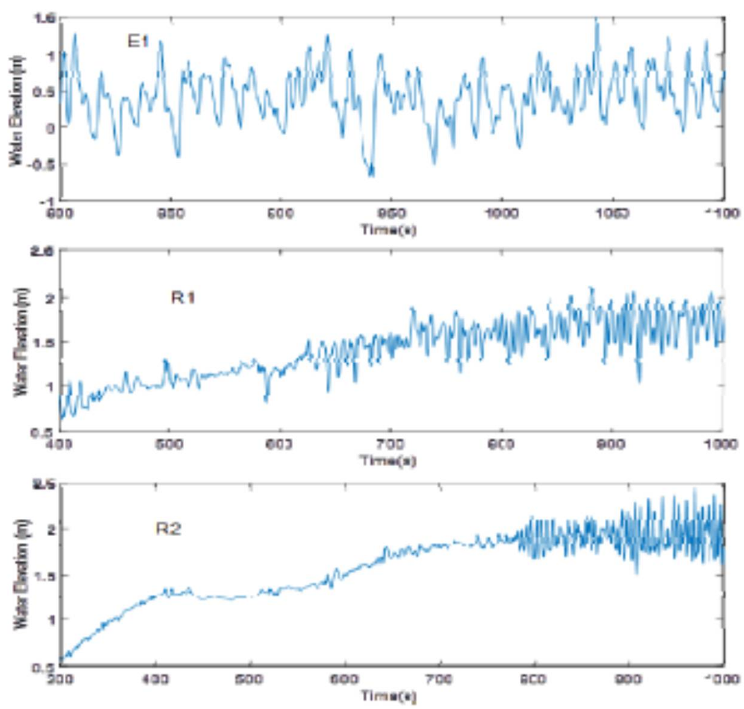


Figure 9. Time series at points E1, R1 and R2 in the river

Located at the estuary, the surface elevation of E1 mainly performs to be irregular wave motions with slight mean level variations. That means, under the wave and discharge conditions of this case, waves from open seas control the estuary dynamics rather than the run-off from inland.

Located in the upstream river, R1 and R2 possess similar features of surface variations, both performing to be rising curves loaded by short wave vibrations. The elevation rises from 0.5 m to 1.7 m at R1 and from 0.5 m to 2.0 m at R2. Closer to the estuary, waves can go upstream to R1 all the time but become large evidently near the 11^{st} minute, when local water level rises to about +1.4 m. While, located further upstream, waves from estuary can hardly arrive at R2 until the 13^{rd} minute, when local water level rises to +1.9 m.

SWASH model results show that, storm surge and wave set-up can push the waterline forward 40 meters to the backshore, approaching the front of coastal buildings, (Fig. 6, right snapshot). Meanwhile, large waves may aggravate the flooding disaster that the wave uprush can reach to +1.5 m above the still water level on the beach and impact the buildings, (Fig. 8). Upstream discharges make inland inundations over the streets and plain with a flooding area of about 1500 m^2. Surface elevations in the river perform to be gradually set-up curves mainly controlled by upstream discharge. While, the water level in estuary area is mainly affected by the waves in the shore.

CONCLUSIONS

Within this study, the use of various numerical tools for simulation of flooding and inundation in residential coastal areas has been investigated, and demonstrated in this paper for a case area of Asparuhovo-Karantina, near Varna, Bulgaria.

One approach use MIKE21 (MIKE FLOOD) numerical tools for simulation of inundation in areas with complex topography and bathymetry. The results obtained for the case area are in good correspondence with the provided statistical & field observation data that gives reason to use this approach when developing coastal flood protection projects.

Another approach has been demonstrated to simulate compound coastal flood by wave transformation in coastal area using SWASH model. Results indicate that, the shoaling effect near shore and wave run-up and wave breaking in the swash zone may aggravate the flooding disaster on the beach, especially when a severe storm generate intense water level rise.

The results obtained by the two approaches are comparable. They have demonstrated the applicability of the chosen approaches for forecasting of flood inundation, as well as for flood mapping and flood risk assessment in urbanized coastal and estuarine areas. This encourages authors for further research and improvement of the demonstrated approaches.

Further research will be focused on the composite modeling approach that will include use of the selected numerical tools in combination with large-scale physical modeling test, and field observation data for detailed calibration and verification of the numerical simulation results.

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REFERENCES

1. Sutherland, J., & Barfuss, S. L., Composite Modelling: Combing Physical and Numerical Models, 34th IAHR World Congress. Brisbane, Australia: HR Wallingford, 2011
2. Vyzikas T., Application of numerical models and codes, WP3 BP Report, MERiFIC Project, University of Plymouth, Feb. 2014, www.merific.eu