Proceedings

Geohazards

Engineering Conferences International *Year* 2006

A Hydrodynamics Perspective for the 2004 Megatsunami

Costas E. Synolakis
University of Southern California, Tsunami Research Center,
costas@usc.edu

A hydrodynamics perspective for the 2004 megatsunami.

Costas Emmanuel Synolakis

Tsunami Research Center, Viterbi School of Engineering
University of Southern California, Los Angeles, California 90089
and
Laboratory of Natural Hazards
Technical University of Crete, Chanea, Greece 73100

The megatsunami of 26 December 2004 was the first tsunami with transoceanic impact since the 1960 Great Chilean and 1964 Great Alaskan tsunamis. Because of the distribution of deaths among a large portion of the nations of the world, the 2004 Boxing Day tsunami is the first universal natural disaster of modern times. For the purpose of adequate mitigation of future tsunamis, it is important to understand which factors control most critically the final characteristics of the flooding, namely runup and inundation. Their successful modeling requires not only a credible database of inundation parameters, against which models can be tested through numerical simulation of the generation, propagation to the local shores, and final interaction of the tsunami with the target beaches, but also in situ observations that help identify unusual impact and previously unrecognized or controversial flow patterns. Here, I comment on the hydrodynamic lessons -mostly relearned- and describe remaining challenges.

Substantial progress in hydrodynamic science has been possible in the past fifteen years only through tsunami field surveys that have driven the basic research (Synolakis and Bernard, 2006). Field surveys have been instrumental in the development of models, as tsunami science evolved differently from research in other extreme natural hazards - there had been no instrumental recordings of tsunamis in the open ocean until recently. Before 2003, and the first ever real time tsunami forecast (Titov et al, 2005a), science stood where earthquake science and engineering were prior to the 1971 San Fernando, California earthquake. Tsunami engineering still does. Field surveys have not only suggested a revisionism of the prevailing paradigm of leading elevation waves, but also identified (as early as 1992) the deficiencies of the hydrodynamic models of that time, leading the their substantial improvement (Synolakis and Okal, 2005). In combination with large scale laboratory experiments (Liu et al, 1991, Yeh et al, 1996, Liu et al, 2005), field survey data sets have allowed for model verification - the process of examining how well a particular approximation of the equations of motions models geophysical reality.

Synolakis (2006) summarizes quantitative field studies describing the impact of the megatsunami in Indonesia, Thailand, Myanmar, India, Sri Lanka, Oman, Somalia, Kenya, Madagascar, the Maldives, Rodrigues, Mauritius, and Reunion. In terms of a timeline, the very first survey appears to have been that of Borrero (2005), in Banda Aceh, documented further by Borrero et al (2006), as augmented with data from later surveys. These surveys identified extreme runup >30*m*, extreme flow depths > 9*m* and extreme inundation distances >3*km*, earlier suspected for extreme historic tsunamis, but with the exception of the 1946 event which produced runup >42*m* in the steep cliffs of Scotts Cap, measurements of such a magnitude had never been documented with modern methods for tectonic tsunamis. It is notable that coastal engineers and geophysicists went to analogous extreme lengths to gather ephemeral data, e.g. the perilous survey of Fritz and Borrero (2006a) in lawless Somalia.

The fortuitous availability of satellite altimetry recordings and satellite images have introduced a new perpective (Geist et al, 2006a). The former, in the verification of the veracity of tsunami generation and propagation models - before the megatsunami, the size and steepness of large tsunamis in the open ocean was suspected and widely believed small, but never really proven so. Model "validation" had only involved comparisons with tide gauge data, without ever accounting for either the instrument response or its specific siting which significantly affects its measurements. Tide gauges had been treated as seismometers, instruments with known and standard response functions. Satellite images have helped not only plan the tsunami surveys, but in conjunction with ground-truth measurements they have allowed for more comprehensive damage assessments.

As Synolakis and Bernard (2006) have argued, a recurring question among all pre-2004 Sumatra tsunami scientists has been what else could had been done from the basic science viewpoint to have reduced the disaster. Given that the hazard had not been identified earlier, the deconstructionism is mute. Had the hazard been known, engineering methods existed to have produced inundation maps depicting possible flooding zones from a variant of the 2004 event, everywhere across the Indian Ocean. After all, widely publishized simulations (Titov et al, 2005b) were rapidly prepared in the immediate aftermath, without even field measurements for guidance, and eventually published with little changes (Titov et al, 2005b). Education campaigns might had been undertaken to better acquaint people everywhere with what was a possible, however unlikely, worst case flooding event. Even a crude tsunami warning without tsunameter data might had been taken seriously. A far easier question is which specific lessons learned and advances in our understanding of tsunamis might had helped reduced the impact.

I will thus summarize my perspective of what has been mostly relearned or just learned, in terms of imagery, man made modifications to the coastal environment, the observations of the polarity of the wave, the verification efforts of numerical models, the inferences from comparisons of the 2004 and 2005 tsunamis and the remarkable observations of impact in farfield ports hours after the first tsunami arrival. This presentation follows closely Synolakis (2006).

The impact of photographs and videos of the advancing tsunami.

Possibly the most glaring surprise was the hundreds of pictures in Phuket of tourist just casually watching the onslaught of the tsunami within 100*m* off the shoreline. Undoubtedly most perished. The images of the aftermath were practically indistinguishable from photographs from the fifteen events since 1992. The response of local residents and tourists in 2004 was unfamiliar, at least for post 1998 tsunamis in the Pacific Ocean, where local residents are more informed of tsunami hazards. Neither the pre-existing tsunami folklore, recorded in numerous popular--science books since 1946, nor the telling Manzanillo pictures (Borrero et al, 1995) and the change of the scientific paradigm for the leading wave of tsunamis (Tadepalli and Synolakis, 1994, 1996) had reached the wider public, worldwide. This is hardly surprising, given the reality of late 20th century scientific discourse in coastal hydrodynamics, where few studies benefit from the experience of others, the perennial wheel remains rediscovered. The focus has been on moving forward rather than sideways, and coastal engineering remains one of the least cited fields in ISI.

In addition to the photographs, there are numerous videos of the advancing megatsunami. For perspective, the only movies that had been available of tsunami evolution on dry land were a short clip of the 1946 tsunami, amateur footage showing the 1983 Japan Sea tsunami and a brief footage of the Camana, Peru 2001 wave. The latter two have been filmed from far away and do not depict the characteristics of the advancing wave well. By contrast, the videos of the megatsunami in Aceh, Thailand, and Sri Lanka allow for more quantitative evaluation of the moving tsunami front and underscore its debris flow nature, in contrast to videos from the Maldives, where the tsunami manifests itself in a manner resembling riverine flooding.

Indeed, Borrero et al (2006) have described the velocity changes of the advancing wavefront as inferred from an amateur video filmed near the center of Aceh, where the flow depth was $2.5m$. The team found the exact locations where the photograph stood during the tsunami attack. By using particle image velocimetry techniques, and discarding parts of the video with active zooming or photographer movement, they were able to infer that the moving front at first moved at a speed of $2m/s$, then suddenly accelerated to speeds $> 5m/s$. Whether this sudden increase is due to a subsequent wave arrival or to a gravity--current type behaviour, where the main bulk of the current is known to move faster than the leading edge, this remains to be explored.

Footage from Thailand shows the tsunami first slowing down as it evolves through increasingly swallower water, then accelerating past the original shoreline. With hindsight, this should had been anticipated, the wave slows down as the depth diminishes, but once on dry land it moves at first with a velocity that is related to the bore propagation speed, before decelarating again as it reaches its maximum runup. These inferences help explain the apparent mesmerization of victims who are seen to simply stand watching the tsunami approaching - clearly its speed did not appear too threatening, until it was way too late.

The effect of human modifications and poor land use to the severity of tsunami impact.

Less surprising as a concept, but not so in terms of impact, were the effects of human modifications and poor land use in enhancing tsunami risk. By their very nature, long waves were not supposed to be so exquisitely affected by features several order of magnitude smaller than their wavelength. In one extreme tides flood indiscriminately of small--scale features, at the other end, storm waves are very responsive to the these scales. Many tsunamis resemble a fast receding and then fast moving tide, or vice versa, yet their interaction with coastlines resembles more that of storm waves, particularly on gentle beaches.

The reef fronting the devastated El Transito during the Nicaraguan 1992 event had an opening to allow for easier navigation, hence its rapid development as a fishing village. The adjacent Playa Hermosa that was largely spared did not. During the 1993 tsunami at Aonae a manmade dune and about 50 concrete wave protectors channeled the tsunami into the populated portions of the town, while protecting the unpopulated areas. In Sri Lanka, the “Sumudra Devi”, a passenger train out of Colombo, was derailed and overturned by the tsunami killing more than 1,000 (Liu et al, 2005, Goff et al, 2006). In the immediate fronting area, significant coral mining had occurred, related to tourism development (Fernando et al, 2005).

In Patong Beach, Thailand, a 60*cm* high seawall separating the beach from the road reduced impact velocities. (Dalrymple and Kriebel, 2005). Mangroves were observed to have protected coastal communities in south--eastern India (Danielsen et al, 2005), while similar conclusions have been drawn by Jackson et al (2005) in the Seychelles. In Thailand, mangroves previously covered some 3,680 km^2 in 1961, declining to only 2,400 in km^2 by 2002. Chang et al (this volume) combine satellite imagery of the impact in Thailand with data from VIEWS, a laptop-based portable field data collection and visualization system for disaster reconnaissance to collect geo-referenced damage observations and footage. They were able to correlate the tsunami impact between adjacent sites - those protected by mangroves experienced damage of 5 in a 12 point scale, those "exposed" a 9, conclusions are consistent with Siripong's (2006, this volume.) It is clear that the effect of mangroves in reducing impact needs revisiting - earlier laboratory experiments have been inconclusive, possibly due to scale effects, it is incredibly difficult to scale frictional dissipation from small scale obstacles correctly. A concept so intuitively obvious has not received the attention it deserves.

In the 1994 East Javan and 1996 Peruvian tsunamis it had been observed that coastal dunes limited the amount of tsunami penetration, although, then, there had been no human settlements to be impacted. In Karon Beach, Thailand, a low sand dune did protect the area behind it (Dalrymple and Kriebel, 2005). In Yale, Sri Lanka a resort, for the purpose of better scenic views, had removed some of the dune seaward of the hotel. The hotel was entirely razed to the ground. Substantially larger water elevations and greater damage observations were found in the hotel grounds as compared to neighboring areas, behind unaltered dunes. Earlier analytical work was suggestive that in many cases the last topographic slope long waves encountered as they attacked composite beaches affected the runup to first order, and it was further inferred that other small scale features do so as well (Kanoglu and Synolakis, 1998).

Low lying coastlines as in Banda Aceh or Hambandotta, Sri Lanka have been known to be particularly vulnerable to tsunami attacks. In the context of inundation mapping in California, it had been observed that areas that get severely flooded during El Nino events, such as Seal Beach, California feature the longest inundation distances when exposed to scenario tsunamis. Areas where waves can attack from two sides are very prone to severe inundation, even from small tsunamis, e.g, East Java 1994, and Peru, 1996. Despite the Boxing Day tsunami being the fifth to hit Indonesia in 13 years, the population was unprepared and was decimated in the low lying area between Banda Aceh and Longhka.

If the tsunami community appeared at first unprepared in the aftermath of the Boxing Day tsunami, it was not due to the failure of paradigms, because of the unprecedented loss of life, the worst possible surprise (Synolakis and Bernard, 2006).

The impact of well-distributed geographically tide gage recordings.

In terms of basic hydrodynamics, the megatsunami allowed for the validation of the model proposed by Tadepalli and Synolakis (1994, 1996) for the leading wave of tsunamis. By considering a step-function type seafloor rupture over constant depth, they had suggested that the leading wave of a tsunami striking the adjacent coastline would cause the shoreline to retreat, naming in a leading elevation N-wave or LDN. The wave propagating off the uplifting part would be a leading elevation N-wave or LEN. This model that remained controversial for quite awhile in the middle 90s. To wit, senior scientists had publicly disputed the existence of the LDN waves by dismissing historic observations as folklore - this was just two months before the Manzanillo tsunami and the now famous photograph of the bay emptying taken as the tsunami arrived. The latter had been the only photographic evidence of the LDN. The controversy was due to the lack of quantitative free field tsunami data - earlier hydrodynamic analysis had assumed much steeper “tsunamis” than those that occur in nature. Eyewitness accounts east of the rupture in Aceh, Malaysia and Thailand have confirmed the first arrival as an LDN, while on the west in India, Sri Lanka, Africa and the IO islands, the megatsunami was noticed mostly as an LEN. Tide gage records have confirmed the eyewitness accounts, refer to figure 1.

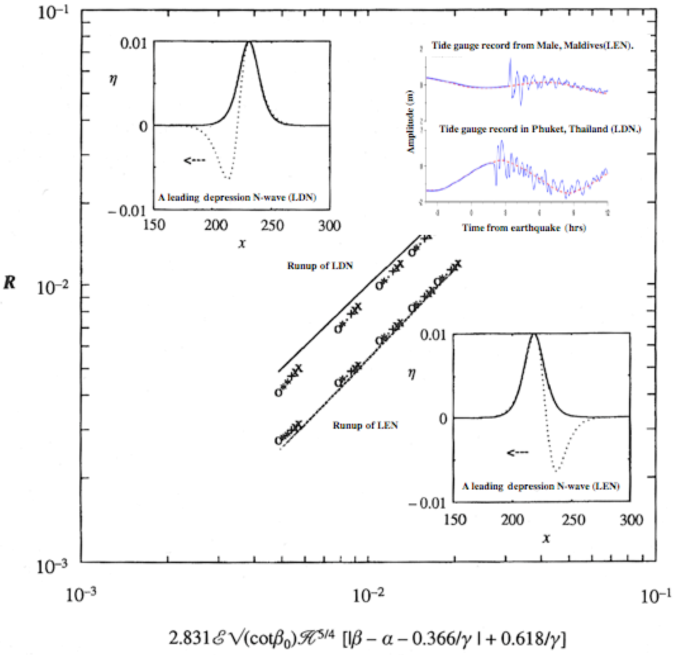

Figure 1. Comparison of the normalized run-up of N waves with predictions from asymptotic results and integral expressions. The data points indicate evaluations of the solution integrals for different beach slopes, the solid line the asymptotic prediction shown in the abscissa. The inset(upper left) shows the profile of a leading-depression N-wave (LDN), the inset on the lower right, a leading elevation N-wave (LEN). ε is a scaling parameter to allow comparison with solitary waves of the same height H and wavenumber γ. $\alpha-\beta$ is the distance between crest and trough. The solitary wave profile is also shown superposed on the N-waves in each inset. After Tadepalli and Synolakis (1994). The inset on the upper right shows tide gauge records in Male and Phuket, after Satake (2005). The 2004 Boxing day tsunami is seen to manifest itself as an LDN in Phuket, as elsewhere east of the subduction zone, and as an LEN in Male, west of the subduction zone.

The impact of satellite altimetry measurements.

Hydrodynamic propagation models are initialized with seafloor displacement estimates derived from fault solutions. Their predictions reflect the accuracy of standard elastic half-space models used to transfer fault solutions to displacement fields. Model initialization had been partially validated with smaller tsunamis, but never with megathrust events. The current state-of-the-art hydrodynamic propagation engineering codes appear to model tsunami propagation adequately.

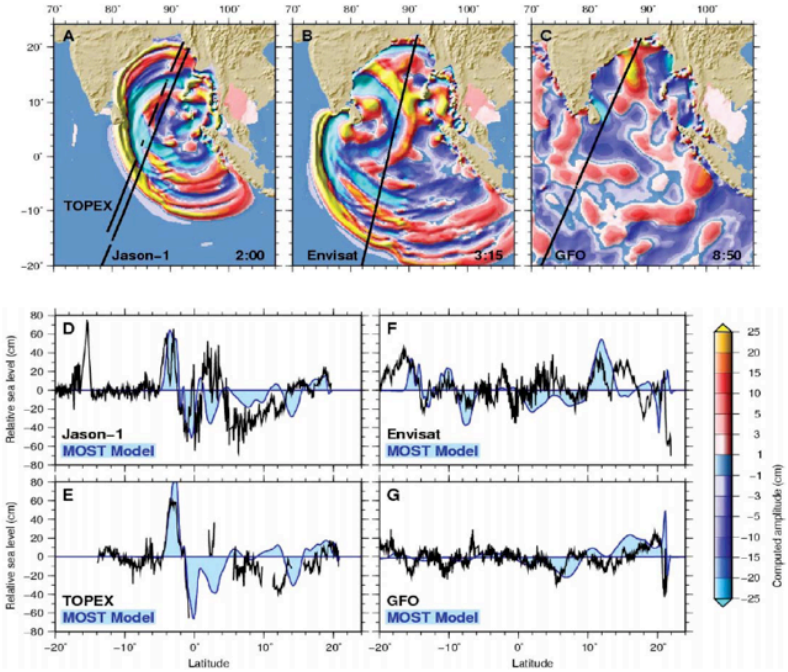

Figure 2 Smith et al (2005)'s comparisons of tsunami free-field signatures from satellite backscatter data with the predictions of the model MOST, believed to be the first of this kind.

Figure 2 from Smith et al (2005) compares tsunami free-field signatures from satellite backscatter data with model predictions from MOST (Titov and Synolakis, 1998), the first ever such comparison. Note the <60*cm* height of the tsunami as it propagates and the small steepness, which confirms the conjecture that led to the development of the LDN/LEN paradigm (Tadepalli and Synolakis, 1996). These comparisons suggest confidence in the models that had been used to estimate the impact of other megathrusts, such as Cascadia.

Newly identified "phenomena".

There have been four noteworthy phenomena not as obvious in earlier tsunamis. One, the sparing of the Maldives, an archipelago with coral atolls which rise to no more than 2*m* (at best) from mean water level. The islands rise from the seafloor as pillared structures, and there was no significant wave amplification (Synolakis et al, 2005, Fritz et al, 2006b)While the reef fronting the islands determined the extend of inundation, there is little question that the Maldives experienced a tsunami with heights closer to the free field tsunami height. A similar conclusion can be drawnn from the impact in Diego Garcia (Synolakis, 2006). While not explicit, this behavior was implicit in Kanoglu & Synolakis (1998).

Two, the wave--guide type effect from mid--Ocean ridges, that appears to have funneled the megatsunami away from the tip of Africa (Titov et al, 2005b). The simulation, not only confirmed the analysis of Ben Menahem and Rosenman (1972) as to the directivity of a rupturing source, but also the overall accuracy of hydrodynamic models in terms of arrival times and quantitative propagation.

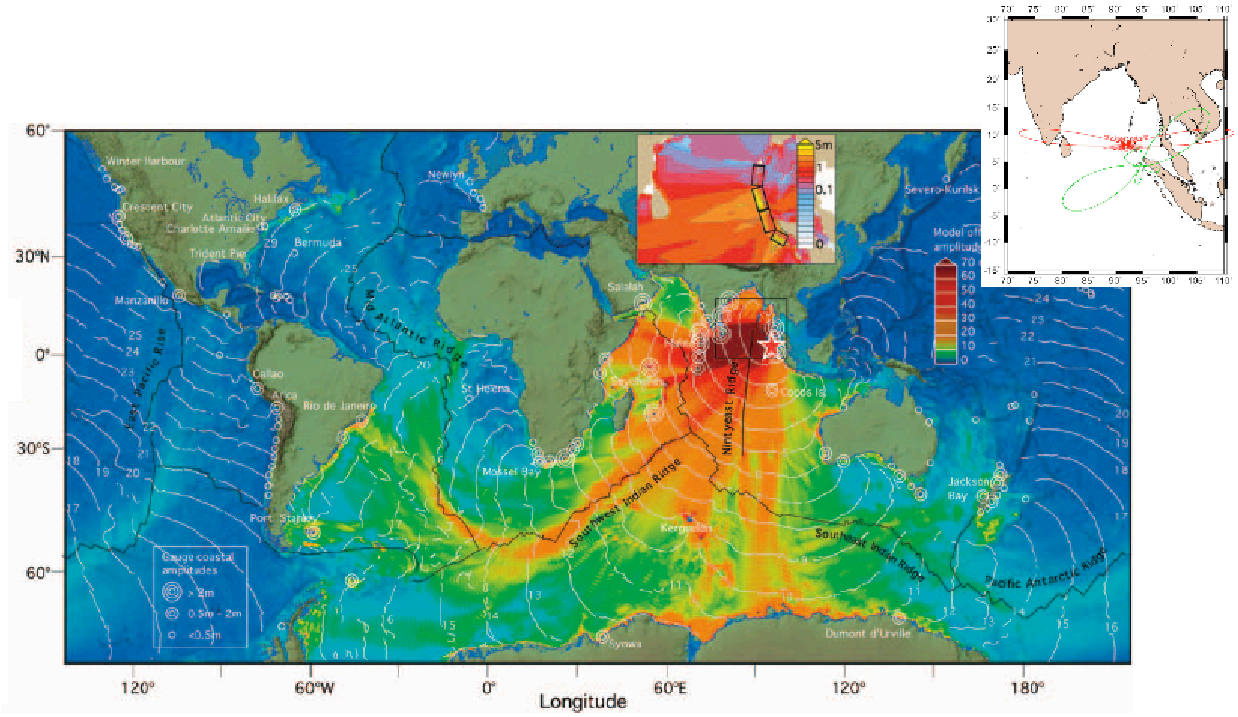

Figure 3 Titov et al (2005b)'s comparisons of the maximum megatsunami height as it propagated around the world, using the model MOST. The white lines are isochrones, lines of equal propagation time. The color chart shows the tsunami height, with dark red 60*cm* and yellow 20*cm*. The inset on the left the composite fault model used in the simulation. The inset on the right Okal's (pers. comm.) calculation of the directivity patterns of a long megatsunami source, as eventually accepted, and from a shorter source, as initially proposed. This figure was originally used to bolster the hypothesis of a longer rupture, and the simple radiation pattern of a long source is seen to agree with Titov et al's (2005b) detailed computations.

Three, the comparison between the 26 December 2004 and 28 March 2005 tsunamis allowed for the quantitative evaluation of the utility of relying on coastal gages. The 2005 tsunami was very small, a "no show" (Kerr, 2005), yet it was triggered by a magnitude 8.7 thrust earthquake, "with similar focal mechanisms, focal depths, and epicenters only about 110 *km* apart" from the megatsunami source, Geist et al (2006b). The latter have published a comparison of maximum wave height measurements as recorded in tide gages in Sri Lanka, the Maldives and Cocos Island, as shown in table 1. While the former values are up to five times larger, if one relied on the measurement from the Cocos Island tide gage, one would infer that the 2005 tsunami was about one-half the size of the 2004 wave. Indeed, there was massive panic in several nations in the Indian Ocean, and the Cocos Island recording did not help cancel the evacuations or better focus the warnings The tide gage in Manzanillo Mexico recorded the 2004 tsunami as 2.8*m* high, as big as the Colombo, Sri Lanka station. Without belaboring the obvious further, the observations underscore the risk of relying on tide gage records for warming guidance. Tide gage measurements are known to be affected by harbor resonance (Raichlen, 1966, Synolakis, 2002). The only proven methodology for inferring the free field height of a tsunami is using tsunameters (Titov et al, 2005a).

Station	26 Dec 2004	28 Mar 2005	Ratio
Colombo. Sri Lanka	> 2.7m	0.5m	>5.4
Hanimaadhoo, Maldives	2.2m	0.4m	5.5
Male, Maldives	2.1m	0.2m	10.5
Gan, Maldives	1.4m	0.3m	4.7
Cocos Island, Australia	0.5m	0.2m	2.5

Table 1. Comparison of tide gage maximum height recordings for two tsunamis, the 26 December 2004 megatsunami and the no-show tsunami of 28 March 2005, after Geist et al (2006b).

Geist et al (2006b) have attributed primarily the nanosize of the 2005 tsunami to the smaller ocean depth over the deformation zone. By contrast Arcas and Synolakis (Kerr, 2005) have argued since most of the deformation occurred below the islands of Nias and Simeulue, the effective water mass set into motion during the 2005 event was reduced, thereby drastically limiting the size and impact of the generated tsunami. Regardless, this controversy underscores the need for pre-existing inundation maps for realistic scenario events, so earlier unrecognized effects such as the presence of islands in the deformation zone can be properly evaluated in advance.

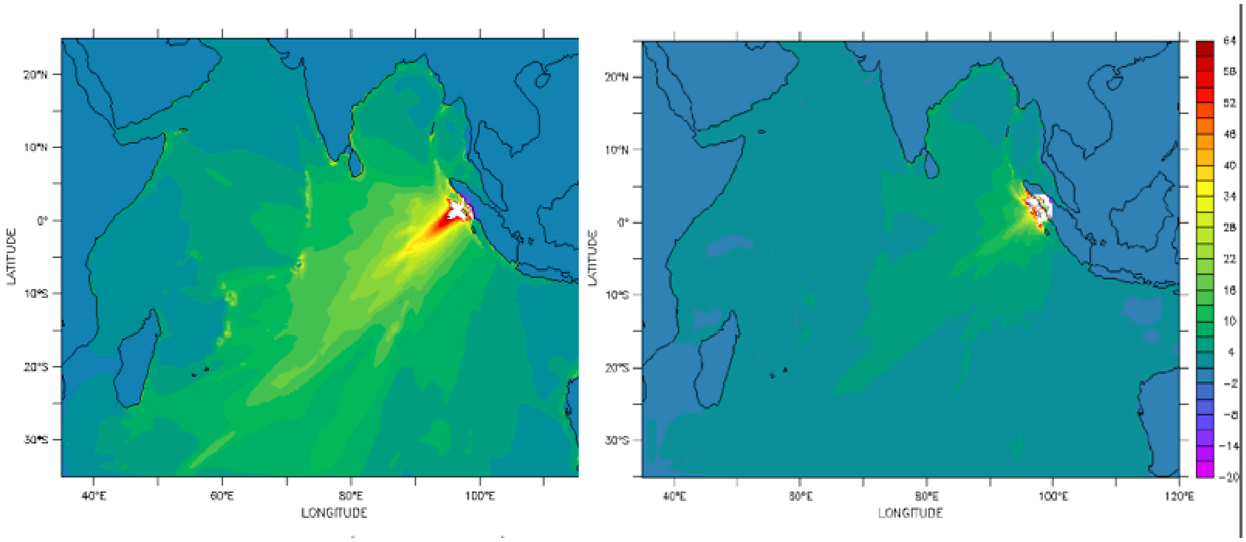

Figure 4. Calculations of the hydrodynamic propagation of the 28 March 2005 event. after Arcas and Synolakis as reported by Kerr (2005). On the left, with the islands of Nias and Simeuleue removed, on the right with the islands in place. The color scale on the right depicts wave heights in cm.

Hydrodynamic observations in Ports in the Indian Ocean from the 2004 tsunami.

The port of Salalah is one of the major container terminal facilities in the Middle East. Okal et al (2006b) report that the 285*m* freighter Maersk *Mandraki*, broke her moorings at 1:42 p.m, and drifted for several hours, both outside and inside the harbor, caught in eddies - all efforts to free her with tug boats were in vain-eventually settled outside the harbor. Similarly, the 292*m* long Maersk *Virginia*, comparable to *Mandraki*, was rocked by the tsunami and had to wait about 7*hrs* outside. During that time *Virginia* was getting pulled towards the breakwater, striking it eventually. Miraculously, *Mandraki* did not collide with other ships or harbor structures. It is interesting to note that the runup in area surrounding the port was less than 1*m,* underscoring the substantial impact that even small tsunamis can have in modern ports.

A similar observation was made in the port of Toamasina, Madagascar by Okal et al (2006a). At the time of first tsunami arrival, around 12:30pm, the runup locally didn't exceed 60*cm*. Yet, around 7:00pm, a 50*m* freighter broke its moorings, and wondered within the harbor for the next 3*hrs*, eventually being grounded on sand bar. Okal et al (2006c) also descrive how the MSC *Uruguay*, anchored in Le Port in east Reunion broke its mooring 4*hr* later than the first arrival, This delay could be attributed to harbor resonance whose onset is triggered by the arrival of waves with periods close to those of the port, and not necessarily by the first wave.

Eskijian (2006) has reported on the damage in Ports in Chennai on the mainland and Port Blair in the South Andaman island. Chennai had no prior warning, no action plan and was totally unprepared. By contrast, in Port Blair, the protocol was that if an earthquake occurred, all vessels were required to leave the port, as soon as possible. Most vessels were able to depart, and there was little damage to the port infrastructure, as a direct result of the tsunami. The tsunami arrived in Chennai 1*hr* 25*min* after hitting Port Blair. Eskijian (2006) speculated that the satellite dish had been rotated due to the earthquake and communications with INSAT 3C lost. Synolakis (2005) has argued that because of the damage to a navy facility, some communications are known to have survived, and that it remains unfathomable that there was no warning issued for the mainland or Sri Lanka. Thousands of people might have been saved, as there was sufficient time of more than 90min to allow for evacuations of the most populous coastlines.

The impact of smaller tsunamis on ports remains highly controversial. Borrero et al (2005) have reported on possible impacts in the Ports of Los Angeles/Long Beach, California from a locally-triggered tsunami of size larger than observed in most IO ports. Their estimates of the economic impact have been scrutinized, in letters to the editor. Nonetheless, the Ports are re-evaluating their emergency preparedness practices, and not a moment too soon, given the observations in the Indian Ocean.

What remains to be done.

What remains in terms of emergency management and warning is discussed by Bernard et al (2006). Clearly tsunameter measurements are not only needed for real time forecasting and warning, but also to quantify what is still an inexact science in terms tsunami magnitude scales. The 1+1 and 2+1 tsunami wave evolution is by now well understood, with uncertainties arising only from the seafloor-water wave motion coupling that initializes the models and the correct choice of model.

One, tsunami numerical models must continue to improve through a combination of testing with benchmark laboratory data, instrumental tsunameter recordings, and field inundation measurements. Specific emphasis needs to be given to the seafloor/wave interaction. There is still little understanding of the dynamics of submarine mass movements, with some claiming speeds of over 100m/s on the seafloor. Differentiation is needed between research and operational modeling, and hopefully eventually there will not need to be. Until then, validation standards urgently need to be established, there is now more than ever greater risk of over--reaction than vice-versa.

Two, the forces on structures need to be better understood, particularly since tsunami floods are often debris floods. Existing methodologies are based on riverine flooding results, and there is little understanding of impulsive or impact loads of small duration. Given the survival of places of worship, and their likely use as shelters in the future, whether planned or not, comprehensive simulations need to establish how safe they really are.

Three, the shortcomings in the population and emergency response observed underscore the urgent need for a worldwide educational effort on tsunami hazards mitigation. Even in 2006, earthquakes in Tonga and off Kythira island, Greece produced strong ground shaking but did not trigger spontaneous evacuations, as the residents were expecting official warnings. At best, official warnings would had arrived in adjacent coastlines after the first tsunami arrival. Further, simply educating local populations at risk is not enough. In an era of global citizenship, it is important that everyone can identify the precursors of a tsunami attack and knows to evacuate to high ground or inland as quickly as possible, and if not, how to more safely vertically evacuate to well--built surviving structures.

References

Bernard, E.N., Mofjeld, H.O., Titov, C.E., Synolakis, C.E., Gonzalez, F., 2006, Tsunami: scientific frontiers, mitigation, forecasting and policy implications, *Philosophical Transactions of the Royal Society, A,* in press (doi:10.1098/rsta.2006.1809)

Borerro, J., Ortiz, M.,, Titov, V.V., Synolakis, C.E., 1997, Field survey of mexican tsunami, *Eos, Transactions American Geophysical Union* , **78** (8). 85, 87–88. Cover Article.

Borrero, J. C., 2005, Field Data and Satellite Imagery of Banda Aceh, *Science*, **308**, 1596.

Borrero, J., Cho, S., Moore, J.E., Richardson H.W, Synolakis, C.E., 2005, Could it happen here, *Civil Engineering*, **75** (4) 55-65, 133.

Borrero, J.C., Synolakis, C.E., and Fritz, H., 2006. Field Surveys northern Sumatra after the Tsunami and Earthquake of 26 December 2004, *Earthquake Spectra* **22** (S3), June (in press).

Ben-Menahem, A., and M. Rosenman, 1972, Amplitude patterns of tsunami waves from submarine earthquakes, *J. Geophys. Res.*, **77**, 3097-3128.

Daniellsen F. and others, The asian tsunami : A protective role for coastal vegetation, *Science*, **310**, 643.

Dalrymple, R.A., & Kriebel, D.L., 2005, Lessons in Engineering from the Tsunami in Thailand, *The Bridge, Proc. Nat. Acad. Eng.*, **35** (2).

Eskijian, M., 2006 Port and harbord damage from the December 26, 2004 Tsunami and Earthquake in the south India and the Andaman Islands, Seismological Society of America, Special volume on the 100th Anniversary of the 1906 San Francisco Earthquake, in press.

Fernando, H.J.S., J.L. McCulley, S.G. Mendis, and K. Perera, 2005, Coral Poaching Worsens Tsunami Destruction in Sri Lanka, *Eos*: **86**:301,304.

Fritz, H. M., Synolakis, C.E., and McAdoo, B.G., 2006a. Maldives field survey after the December 2004 Indian Ocean tsunami, *Earthquake Spectra* **22** (S3), in press.

Fritz, H. M., and Borrero, J.C., 2006b. Somalia field survey after the December 2004 Indian Ocean tsunami, *Earthquake Spectra* **22** (S3),in press.

Geist, E.L., Titov, V.V., and Synolakis, C.E., 2006a. Tsunami: wave of change, *Scientific Amer*ican, **294**, 56–63.

Geist, E.L., Bilek, S.L., Arcas, D., and Titov, V.V., 2006b, Differences in tsunami generation the Dec 26, 2004 & Mar 28, 2005 Sumatra earthquakes: *Earth Planets Space*, **58**, 185-193.

Kanoglu, U. and Synolakis, C.E., 1998, Long wave runup on piecewise linear topographies, *J. Fluid Mech.,* **374**, 1-28.

Kerr, R., 2005, Model shows Islands Muted Tsunami, *Science,* **308**, 341.

Liu, P.L.-F., Synolakis, C.E., and Yeh, H.H., 1991. Report on the International Workshop on Long Wave Runup, *J. Fluid Mech.* , **229**, 675–688.

Liu, P.L–F., Lynett, P., Fernando, H., Jaffe, B.E., Fritz, H., Higman,B., Morton, R., Goff, J., Synolakis, C.E., 2005, Observations by the International Tsunami Survey Team in Sri Lanka, *Science*, **308**, 1595.

Liu, P., L-F., Wu T.R, Raichlen F, Synolakis ,C.E., Borrero J.C., 2005b Runup and rundown generated by three-dimensional sliding masses, *Journal of Fluid Mechanics*, **536**, 107-144.

Okal, E.A., Fritz, H.M., Raveloson, R., Joelson, G., Pancoskova P., and Rambolamanana, G., 2006a, Field Survey of the 2004 Indonesian Tsunami in Madagascar, *Earthquake Spectra,* **22,** in press.

Okal, E.A., Fritz, H.M., Synolakis, C.E., Raad, P.E., Al-Shijbi. Y., and Al-Saifi, M., 2006b, Field Survey of the 2004 Indonesian Tsunami in Oman, *Earthquake Spectra*, **22**, in press.

Okal, E.A., A. Sladen, and E.A.-S. Okal, 2006c, Field survey of the 2004 Indonesian tsunami on Rodrigues, Mauritius and Réunion Islands, *Earthquake Spectra*, **22**, in press.

Raichlen, F., 1966. Harbor resonance, in Ippen, A.T. (ed.), Coastline and Estuarine Hydrodynamics, McGraw-Hill, New York, NY.

Synolakis, C.E., 2006, India must cooperate on tsunami warning system, *Nature*, **434**, 17-18.

Synolakis, C.E., 2006, Tsunami runup measurements from the megatsunami, *Earthquake Spectra*, **22**, in press.

Synolakis, C.E., and E.A. Okal, 2005, 1992-2002: Perspective on a decade of post-tsunami surveys, in: Tsunami ed. by K. Satake, *Adv. Natur. Technol. Hazards*, **23**, 1-30, 2005.

Synolakis, C.E., Okal, E.A., and Bernard, E.N., 2005,The megatsunami of December 26, 2004, *The Bridge*, (National Academy of Engineering, USA) **35**, (2), 26-35.

Synolakis, C.E., and Bernard, E.N., 2006, Tsunami science before and beyond Boxing Day 2004, *Philosophical Transactions of the Royal Society, A,* in press.

Synolakis, C.E., 2002, Tsunami and Seiche, in *Earthquake Engineering Handbook*, edited by Chen, W.F and Scawthorn, C., CRC Press, 9-1 to 9-90.

Tadepalli, S. and Synolakis, C.E., 1994, The Runup of N–waves. *Proc. Roy. Soc., Lon, A*, **445**, 99–112.

Tadepalli S. and Synolakis, C.E., 1996, Model for the leading waves of tsunamis, *PhysicalReview Letters*, **77**, 2141–2145.

Titov, V.V., and Synolakis, C.E., 1998, Numerical modeling of tidal wave runup, *Journal of Waterway, Port, Ocean and Coastal Engineering*, **124** (4), 157 – 171.

Titov, V.V., F.I. Gonzlez, E.M. Bernard, M.C. Eble, H.O. Mofjeld, J.C. Newman, and A.J. Venturato. 2005a, Real-time tsunami forecasting, *Natural Hazards* **35**(1), 45-58.

Titov, V. V., Rabinovich, A. B., Mofjeld, H. O., Thomson, R. E., & Gonzalez, F. I., 2005b, The global reach of the 26 December 2004 Sumatra Tsunami, *Science*, **309**, 2045–2048.

Yeh, H., Liu, P.F., and Synolakis, C.E., 1996. Long Wave Runup Models, World Scientific, Singapore, 403 pp.