Unsteady Wave-Driven Circulation Cells Relevant to Rip Currents and Coastal Engineering

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Grant Number: N0001406IP20020
Co-Sponsored by NSF as Grant 0423877
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LONG-TERM GOALS

The long term goals of this project are to predict waves, currents, sediment transport and morphological development in the nearshore ocean with accuracy and efficiency.

OBJECTIVES

The technological objectives of this project are to investigate the mechanics of wave-driven flow on complex topographies. Specifically, we are examining the occurrence, forms, and detailed causes of flow instabilities over complex topographies; the influence of three dimensional topographical features on large scale flow features, and the forms and utility of simplified expressions in predicting flows.

APPROACH

The technical approach used here differs for the different sub-goals. The study of wave-driven flow instabilities over varying topographies uses tangent nonlinearities about steady base flows to derive a large stability matrix which is solved for stable and unstable eigenvalues. This may be thought of as extending the body work on shear waves over the past two decades (Holman and Bowen, 1989; Dodd et al., 2000; etc.) to more complex rip current topographies, and with more complex hydrodynamics including wave-current interaction. This work is largely being performed by the PI Kennedy and PhD student Yang Zhang.

The study of three dimensional topographic features on large scale flow patterns is a combination of theoretical and laboratory work. Theoretical work uses generation of circulation arguments combined with vortex dynamics to examine the influence of topographic features on wave driven vorticity transport and the overall flow features. This is compared with existing laboratory data to assess the accuracy of predictions and to describe overall regimes for three dimensional flow based on geometrical and wave parameters. This work is largely being performed by the PI Kennedy in concert with Dr. K. Haas of Georgia Tech and Dr. M. Brocchini of the University of Genoa, Italy, and their students.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Unsteady Wave-Driven Circulation Cells Relevant to Rip Currents and Coastal Engineering**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Florida,Dept of Civil and Coastal Engineering,365 Weil Hall,Gainesville,FL,32611**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

The study of simplified methods for predicting wave-driven nearshore flows uses a scaling approach: comparing dimensionless parameter groups suggested by theory with laboratory, field and computational data. This work is just underway, and relies on data provided by Kennedy, Haas, and E. Thornton, NPS. Other collaborators providing data are likely to emerge in the future.

WORK COMPLETED

Stability studies are the most complete portion of this project. A new solver has been coded to analyze the stability of wave-driven currents over arbitrary topography, and has been applied to a variety of wave conditions and topographies. Initial efforts have concentrated on topographies likely to cause rip currents, as these are known from laboratory and field studies to be prone to strong instabilities, while continuing work will examine flows intermediate between rip currents and longshore currents. Figure 1 shows a typical rip current example with the base velocity field, and underlying topography.

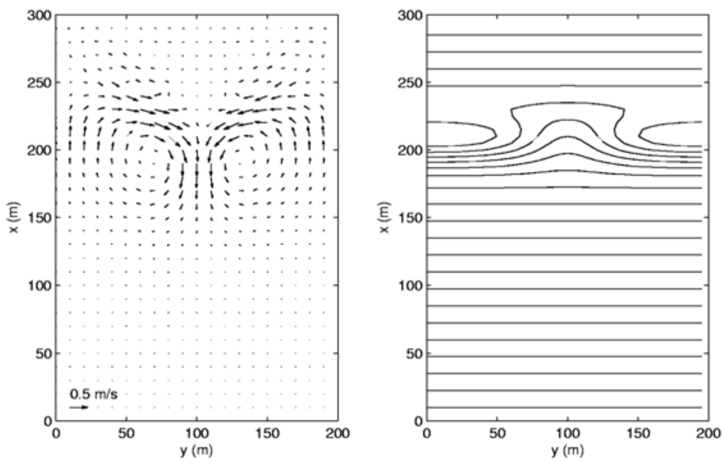

Figure 1. Plan view of base velocity field (left) and 0.5m depth contours (right) for typical wave-driven rip current. The shoreline is at x=300m.

Figure 2 shows snapshots from the fastest growing instability mode, which may be interpreted either as an offshore-propagating antisymmetric jet or as an oscillating circulation cell. The jet instability interpretation is in good correspondence with the theoretical and laboratory work of Haller and Dalrymple (2001), while MacMahan et al. (2003) inferred that the circulation cell was oscillating largely from several point measurements of rip current velocities. Several unstable modes may coexist simultaneously; in particular antisymmetric jet modes often have corresponding symmetric modes whose frequencies and growth rates track closely.

While the unstable jet mode is a classic vorticity driven instability, different unstable modes exist for small waves and weak currents which are entirely due to wave-current interaction, and disappear in its absence. The stability analysis is particularly good at analyzing this type of system as it can separate the changes in mean forcing from wave-current interaction from the stability effects. Figure 3 shows snapshots of the fastest growing wave-current mode, as it is denoted. It appears much like a jet mode, but is forced by the feedback between velocity fluctuations in the jet and the resulting current refraction of incoming waves and breaking patterns, which then amplify the initially small current fluctuations and so on.

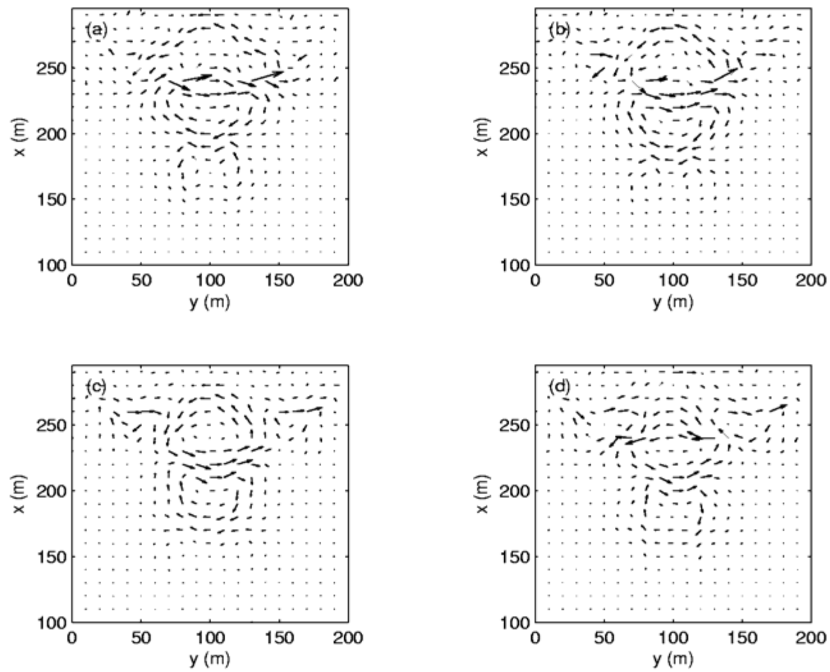

Figure 2. Snapshots of the fastest growing offshore propagating jet instability for the base flow and topography of figure 1. (a-d) σt=(0-3)π/4. The predicted period of oscillation is around 2π/σ=13 minutes with an e-folding growth rate of around 11 minutes.

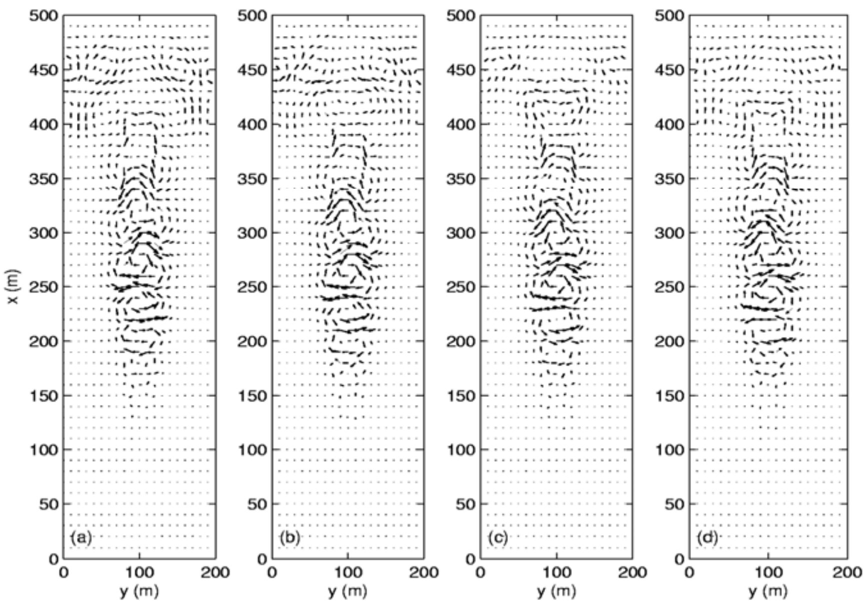

Figure 3. Snapshots of wave-current interaction driven jet mode for weak base flows. (a-d) σt=(0-3)π/4. The predicted period of oscillation is around 2π/σ= 30 minutes with an e-folding growth rate of around 20 minutes. The shoreline here is at x=500m.

Work completed on three dimensional topographic features and their effects on wave driven flows has concentrated on an existing series of laboratory tests of wave-induced currents using identical wave forcing over several different topographies. Results have shown that for these maximum current velocities are quite insensitive to the ratio of bar length/rip channel width, while being strongly affected by wave properties. Figure 4 shows examples of wave-driven flow for very wide and relatively narrow rip channels with identical wave inputs. Although overall patterns are quite different, maximum longshore and cross-shore velocities are quite similar, which may prove quite helpful for predicting flows when detailed field bathymetries are not known.

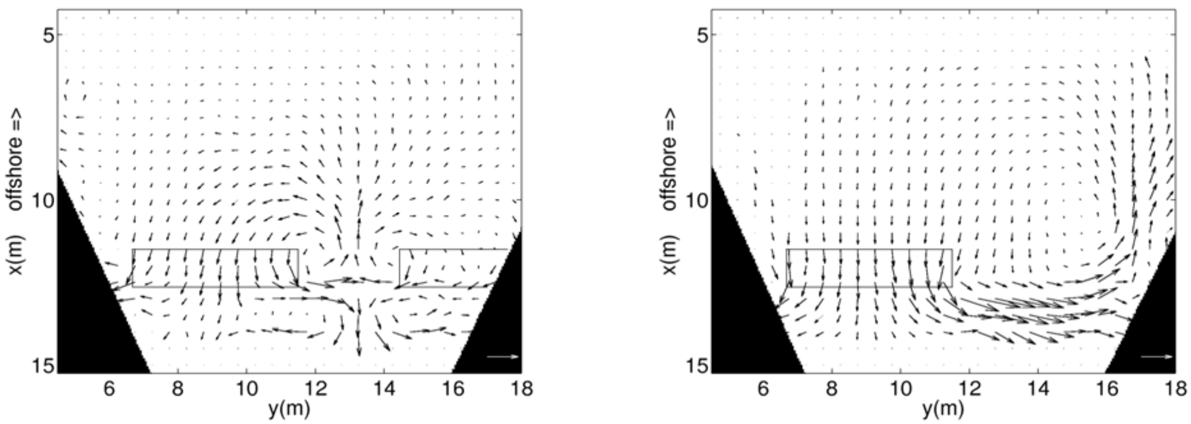

Figure 4. Laboratory results for mean wave-driven flows with identical wave forcings but differing bar lengths. (Left) rip current-type topography; (right) isolated bar with wide channel. Rectangles show the bar outlines. The still water shoreline is at x=15m, while a basin sidewall is at y=18.2m. The small white arrow at bottom right of each figure is 0.5m/s.

RESULTS

For the work on the stability of wave-driven flow, there are several significant results:

- Vorticity-driven antisymmetric and symmetric instabilities are found for a wide range of moderate and strong rip currents. These may be thought of either as an oscillating jet (Haller and Dalrymple, 2001), or as an oscillating circulation cell (MacMahan et al., 2003).

- Instabilities exist for low strength rip currents that are entirely dependent on wave-current interaction. Their basic mechanism is a feedback between rip jet oscillations and the resulting changes in wave breaking patterns. This is entirely different from classic vorticity-driven instabilities.

- The stability or instability of a wave-driven nearshore circulation cell is strongly dependent on bottom frictional dissipation. This reinforces previous findings for shear waves on longshore uniform topographies.

For work on three dimensional topographic effects the most significant result is:

- Maximum longshore and cross-shore velocities are insensitive to some details such as bar length

IMPACT/APPLICATIONS

There are several potential future impacts arising from this work:

1. Stability work will improve understanding of current pulsations for wave driven flow in landing zones which, when matured, may be transitioned into operational use.

2. Stability work may also lead to the development of new Reynolds stress closures for turbulent fluctuations of wave-driven flow, which will be useful in modeling applications

3. Work on the sensitivity of flows to detailed topography may lead to simplified prediction methods for operational use, where the detailed topography is almost never known.

RELATED PROJECTS

This project is co-sponsored by the NSF Division of Chemical and Transport Systems, Fluid Mechanics and Hydraulics Program under grant 0423877.

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