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SHORT COMMUNICATION

# Human instability related to drowning risk in surf zones for novice beachgoers or weak swimmers

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**Abstract** This paper provides qualitative descriptions of the physical mechanisms that can cause human instability in surf zones, where human instability is considered the loss of solid contact between an individual's feet and the seabed. The forces resulting from the combination of waves and currents typical in surf zones present a hazard to novice beachgoers and weak swimmers that is often not recognized by those individuals. A conservative "rule of thumb" is that the deepest water a novice beachgoer should reach, even during the passage of wave crests, is a depth that only reaches the persons thigh, that is, between the knee and the waist.

**Keywords** Drowning · Surf zone · Rip current · Beach hazard

## 1 Introduction

Beaches are an extremely popular recreational destination for tourists and coastal residents. Unfortunately accidentally drowning is one of the risks associated with entering the water (e.g. Klein et al. 2003; Brighton et al. 2013). The risk of drowning at a beach greatly exceeds all other beach-going-related risks, such as shark attacks, and in most regions the risk of drowning on beaches exceeds other weather-related risks to life, such as severe storms. In the USA, an average of 35 individuals drown per year due to rip currents (Gensini and Ashley 2010). A minority of surf-related drowning occurs for experienced visitors, who knowingly engage in risky activities. Teenage males, for various reasons, exhibit higher rates of surf rescues relative to the general population (Woodward et al. 2013). But the majority of drowning victims are naïve regarding the dangers of entering a surf zone, and often they are inexperienced or weak swimmers (Drozdzewski et al. 2015).

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A critical transition for the inexperienced swimmer occurs either when they lose their footing or when the potential victim's face is accidentally submerged under water. The latter can cause ingestion or inhalation of water and/or trigger panic, which can quickly lead to drowning. This fact motivates discussion of the physical processes that cause instability of an inexperienced or weak swimmer in a surf zone. In this work, we provide qualitative explanations of the physical processes in surf zones that lead to human instability and increase the risk of drowning. The goal of this work is to educate and inform novice beachgoers and weak swimmers of the risks associated with entering surf zone waters, in the hope that they avoid behaviors that put them at higher risk of drowning (McCool et al. 2009).

## 2 Hydrodynamic mechanisms for human instability

People usually remain stable while standing in still water as long as their shoulders remain above water, in which case their feet generally remain in contact with the ground or seabed. But when standing in moving water, there are several hydrodynamics mechanisms that cause instability, which can be defined as when a person's feet lose solid contact with the seabed. The loss of footing can occur in two general ways: Firstly, sliding or liftoff may initiate between a person's feet and the seabed due to a combination of hydrodynamic forces and an individual's response to these forces. Secondly, hydrodynamics forces may cause the rotation of a person in a vertical plane, causing feet to move upward off of the seabed and head to move downward into the water. We will refer to the first mechanism as sliding instability and the second as tumbling instability. While sliding instability is not as traumatic or alarming to a bather as tumbling instability, it is the more common occurrence. Once someone's feet lose contact with the seabed, the person is essentially free-floating and can be carried by the current with little sensation of subsequent movement. This is particularly important in rip currents (Dalrymple et al. 2011), where a bather may be carried offshore into deeper water before they realize they are in trouble. Rip currents contribute to a large proportion of surf drownings, and there are a variety of escape strategies that have been suggested for someone caught in a rip current (Bradstreet et al. 2014; McCarroll et al. 2014). The present paper does not specifically address rip currents or escape strategies, but rather focuses on the instability mechanisms that may destabilize a novice beachgoer and potentially lead to their entrainment into a rip current or other dangerous surf situations.

The water motions that cause human instability in the surf zone are associated with both waves and currents. *Waves* refers to surface gravity waves, which are generally formed offshore (sometimes at great distances) and propagate toward the shoreline. Waves cause rapid changes in local water depth, flow speed, and flow direction. As waves approach the shore, they eventually break as their energy is transferred into either turbulence or lower-frequency motions such as surf beat or infra-gravity waves. On gently sloped surf zones waves break to form *bores*, which continue to cause rapid changes in local water depth, flow speed, flow direction, and turbulence levels as they propagate across the surf zone toward the dry beach.

Waves are part of the attraction of the surf zone, so it is common for even novice beachgoers to wish to wade, jump, and play in waves. While the safest advice is to not go into the water, this is not realistic for people who have traveled to the beach specifically because they wish to go into the water! The sudden changes in depth, flow, and turbulence associated with waves are some reasons why waves are attractive to beachgoers (envision body surfing, for example), yet these same factors lead to an enhanced level of risk that is often not appreciated by novice beachgoers.

*Currents*, in contrast to waves, refer to quasi-steady flows generally in the alongshore direction (e.g., tidal, wind-driven, or wave-driven), or less commonly, the off-shore direction (rip current, tidal inlet, or river-driven). Substantial currents without the presence of waves tend to occur in specific and relatively rare locations, and in those locations their occurrence is generally well known as a significant local hazard. These types of locations are normally not the destinations for novice beachgoers.

Human instability due to currents alone (with no waves or insignificant waves) in the surf zone exhibits dynamics fairly similar to instabilities that occur when people are exposed to flood waters on land, or when a bather wades too deeply into a flowing river. There have been several studies of the mechanisms for human instability in floods and tsunami's, and it has generally been found that the product of the water depth and the flow velocity is the most relevant hydrodynamic parameter in predicting human instability (e.g., Abt et al. 1989; Jonkman et al. 2008). In other words, a weaker current in deeper water leads to instability similar to a stronger current in shallower water, where in both cases the water depth is less than the height of a person. The reasons for this are twofold: (1) In deeper water the hydrodynamics forces act upon a greater extent of the victim's body, and (2) deeper water increases buoyancy and thereby decreases the individual's immersed weight that tends to keep feet on the seabed. The typical range of critical values for the flow-depth product for currents to cause human instability ranges from approximately 4–12 $ft^2/s$ (.37–1.1 $m^2/s$). The lower limit of the range is equivalent to a flow speed of 2 ft/s in a water depth of 2 ft, or a flow speed of 1 ft/s in a water depth of 4 ft. The critical value for the flow-depth product in predicting human instability in currents alone is highly variable, and its estimation or application within surf zone environments would probably not be very useful, for reasons to be explained later.

Human instability in the surf zone is usually caused by a combination of waves and currents. The presence of waves in the surf zone in addition to currents is unusual relative to rivers, lakes, or pools. While novice swimmers may appreciate the novelty and attraction of the surf, they also may not recognize the enhanced associated risks. Forces due to waves and currents on stationary structures such as vertical cylinders (like a pier piling) is a well-studied topic, and sophisticated methods exist to predict the forces as a function of time due to various combinations of waves and currents. It is possible to calculate the conditions for stability for a structure in the surf zone, so it is tempting to do so for people. But applying such precise and sophisticated predictions to the question of human instability in the surf zone would be somewhat misleading, because of the wide variety of differences between a human being and an inanimate structure.

Nevertheless, it is well known that waves have a very influential role in causing human instability in surf zones. The presence of waves causes temporal variations in buoyancy (in the vertical direction), and horizontal forces due to both flow and pressure. The peak forces due to waves depend upon wave characteristics such as height, period, and shape, and they often exceed the forces due to currents. The buoyancy force and the horizontal forces due to waves combine with the currents to promote instability. Stated more simply, the presence of waves, either alone or in combination with a current, induces human instability at even shallower water depths than a current would alone.

Given the considerations expressed above, the flow-depth criterion can be applied to the surf zone in a conservative sense in the following manner. The maximum flow velocity due to a bore in the surf zone is given approximately by $(gh)^{1/2}$, where $g$ is the acceleration due to gravity and $h$ is the mean water depth. The flow-depth product is then equal to $g^{1/2}h^{3/2}$. Applying a critical value of 1 $m^2/s$ for the flow-depth product suggests a critical depth for human instability of approximately 48 cm, or 18 in. Due to the limitations to be discussed later, this value can only be considered an order of magnitude estimate, which admittedly is not particularly useful.

## 3 Complications due to human factors and environmental conditions

There are a wide variety of human and environmental factors that complicate the application of a precise value of a critical parameter for human instability in the surf zone. On the human side, characteristics such as body shape, size, mass, balance, strength, foot size, state of mind, and body response all have influence. Body response, in particular, can have a strong influence. For example, a common intuitive human response is to turn sideways to minimize one's cross-sectional area exposed to a wave or current; this can help minimize the drag forces and also provide better foot position to help maintain stability. On the other hand, people often make a small hop when a wave approaches, perhaps to try to keep their head higher above water, which can lead to instability because of the intentional separation of contact between their feet and the seabed.

With regard to environmental conditions, the substrate (smooth, rough, slippery, sticky, etc.), slope, and flow variations in time all have an effect on human stability (e.g., Xia et al. 2015). Often surf zones exhibit bathymetric features such as steps, bars, holes, and bedforms. These sudden changes in depth or slope are generally not visible, and they can contribute significantly to a person's loss of balance.

There have been several attempts to incorporate some of these factors into developing instability criteria in floods that could be applied to different individuals in different environments (Jonkman and Penning-Rowsell 2008; Xia et al. 2014). This formidable task is of questionable utility in terms of preventing potential surf zone drownings, due to the large number of highly variable human and environmental factors and the lack of awareness by the victims to the variety of risk factors in any given situation.

## 4 Two US site examples

Daytona Beach, Florida, and Ocean Beach, San Francisco, California, are examples of beaches in the USA where unfortunately people have occasionally drowned. Both are gently sloping sandy beaches that are popular with local residents and also with tourists. Both Daytona Beach and Ocean Beach generally have lifeguards and sign/flag warning systems during normal operational hours, and beachgoers are strongly encouraged to heed the warnings.

Daytona Beach is located on the Atlantic Ocean on the east coast of central Florida. This beach is prone to occasional, bathymetrically controlled, rip currents that tend to occur most often during periods of onshore winds, low to medium tides, and shore-normal wave directions (Engle et al. 2002). Rip currents at this non-traditional beach morphology (Van Leeuwen et al. 2016) tend to occur in association with bathymetric lows, or deeper areas, of the longshore bar, which is an approximately linear ridge of underwater sand that is aligned approximately parallel to the shoreline. Waves tend to break less at the relatively deeper areas of the longshore bar, and this region of lower waves sometimes fools bathers into thinking this is a safer region, when in fact the region is more dangerous when there is a rip current present.

Ocean Beach, in contrast to Daytona Beach, is on the Pacific Ocean coast and located southwest of the Golden Gate entrance to San Francisco Bay. This beach is subject to high wave energy, strong tidal currents, and strong wave-driven currents due to the very complicated offshore bathymetry and the Golden Gate inlet (e.g., Shi et al. 2011). Wave and current conditions at this beach can change rapidly, and powerful rip currents occasionally form here. Bathers who lose stability at this beach are often repeatedly impacted by large waves while they are rapidly carried either longshore or offshore due to the strong currents.

## 5 A caution to somewhat experienced beachgoers and intermediate swimmers

While this paper is aimed toward novice beachgoers and weak swimmers, most of the people that enter surf zones are somewhat experienced and intermediate swimmers. That is, they have been in surf zones several times before, and if they lose stability, then can generally regain it or swim to safety under normal conditions. There are two main risks worth mentioning for these people because these risks are severe and tend to be underestimated. The first relates to rip currents, because these can quickly carry a person into deeper (and sometimes rougher) water. This forces the potential victim to swim and stay afloat in more challenging conditions than were expected, which can lead to panic and/or exhaustion. The second hazard for somewhat experienced beachgoers relates to the narrow region in which waves are breaking, because the impact associated with breaking waves can be substantially larger than unbroken waves. Of particular danger are plunging breakers, in which a nearly vertical wall of water can impact a person causing powerful tumbling instability and sometimes strong impact of the head or upper body with the seabed.

## 6 Recommendations for novice beachgoers and weak swimmers

A novice beachgoer or weak swimmer is likely to underestimate the danger of waves and currents in the surf zone, and they should only enter the water in the vicinity of a lifeguard. If there are flags or warning signs placed on the beach, they should learn the meaning of the flags or signs and follow their guidance. Even when following these precautions, an individual that was previously comfortable wading out to chest deep water in a lake, for example, may find themselves toppled in waist deep water in the surf zone. Or an individual who was previously comfortable wading to a depth of 2 or 3 ft in a weakly flowing river may find themselves suddenly unstable in the same depth in the surf zone when impacted by a 2- or 3-foot-high wave. Because waves can occur intermittently and the water depth may vary slowly, a particular water depth that seems safe upon arrival might become unsafe due to rising water or the sudden impact of waves only a few minutes later. Because of the huge variability in people and in beach environments, there are no exact thresholds for human instability that would apply universally in surf zones to keep people safe. Generally, a novice beachgoer or weak swimmer should stay sufficiently shallow that they could wade toward the shore at any time they begin to feel unstable. A good ‘‘rule of thumb" is that the deepest water a novice beachgoer should reach, even during the passage of wave crests, is a depth that only reaches the persons thigh, that is, between the knee and the waist. If an individual senses at any time that they are close to losing stability due to either sliding/liftoff or tumbling, then they should promptly make their way into shallower water. If they are unable to wade toward the shore, then they should immediately wave their arms over their head to seek assistance.

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