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# Numerical simulation of kink zone instability in fractured rock masses

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ABSTRACT

This paper investigates the conditions favourable to the development of a kink zone instability in jointed rock masses in relation with joint properties such as friction angle, frequency of occurrence, and orientation. Numerical simulations using the distinct element code UDEC shows that kink zone instabilities develop when primary joints are oriented from $5^{\circ}$ to $30^{\circ}$ relatively to the major principal stress under confining pressures below 5.0 MPa. Also, results allow the definition of a failure criterion for kink zone instabilities based on geometrical properties related to the dilatancy rate. The failure criterion is $\tau_{KZI} = \sigma_n \tan \psi$ where $\psi$ is defined as the rotational dilatancy angle.



## 1. Introduction

The stability of rock slopes, underground openings and other excavations in intensely foliated or in jointed rock masses, may be at risk with an unusual failure mode by kink zone instability (KZI). This deformation structure is a tabular zone, transverse to joints, bounded by sub-parallel surfaces called kink planes (KP). The "internal" layers (those between the KPs) are sharply deflected and rotated with respect to the "external" ones. This type of instability is developed by buckling instability in brittle, ductile foliated or layered rock. Jointed and fractured rock masses also show the development of KZI as a mode of failure or deformation. Goodman and Kieffer [1] classified this mode of failure as "buckling" and "kink band slumping". Geomechanical designs of excavations in jointed and foliated rock masses rarely take into account such a mode of failure, and very few studies considered this problem.

KZI has been observed within biaxial tests on rectangular block models composed of square cross-section rods, piled up in a staggered joint pattern (Fig. 1) [2–5]. While some important parameters were tested (joints orientation and frequency; confining pressure), paucity of the data lead to incomplete interpretation of the phenomenon. Recently, numerical modelling, using the 2D distinct element code UDEC, has proven to be suitable to simulate the formation of KZI within rock slopes [6,7] and to reproduce numerically physical biaxial tests [8,9]. Various joint parameters (orientation, surface friction, stiffness) and boundary conditions (confining pressure, boundary friction) were tested on the numerical biaxial model [8], but the high deformation rates used simulated more a dynamic loading than a static one. Optimal boundary conditions to simulate KZI in a numerical model under static biaxial loading were determined [9], but no new data on the governing parameters were given.

The present paper considers the effects of the governing parameters (joint frequency, confining pressure, primary joints surface friction, and primary joints orientation) on the jointed rock mass strength and on the KZI's geometry. New results come from numerical simulations using UDEC software, and are compared with physical biaxial tests from the literature [2]. Representation of failure envelopes in the Mohr $\tau$–$\sigma_n$ space leads to the definition of a failure criterion based only on dilatancy.

## 2. Basic concepts of KZI

Kinking is the result of buckling instability and unstable yielding on planes of anisotropy. The main mechanisms of this rotational deformation are passive slip along the planes and simultaneous rotation of these planes. Phenomenological models, geometrical properties, and deformation characterization are developed in the geology literature on kink banding in strongly foliated rock bodies [10–17]. KZIs are characterized by the angular relationships between $\alpha$, $\beta$, $\omega$, $\theta_{KP}$, and the width ($W$) (Fig. 2).

### 2.1. Geometry and formation

Two general models have been proposed to explain the formation of kink bands in highly foliated geological material:

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a ductile "hinge-migration model" [12] and a brittle "rotational model" [14,15]. The hinge-migration model assumes that a kink band is initiated as a small lensoïd structure. At first, it propagates longitudinally and then it widens by lateral migration of the KP during progressive deformation. In this model, it is assumed that the volume and the foliation spacing are conserved so that no dilatancy occurs. This model is dependent upon the concept of an ideal foliated body in which the fundamental mechanism of plastic deformation is glide on closely spaced surfaces parallel to the foliation [12]. Implicit in this model is the folding and unfolding of the internal foliation as the KP change their positions. The rotational model proposes that kink bands forms as segments of constant length rotate between KP of fixed orientation in space.

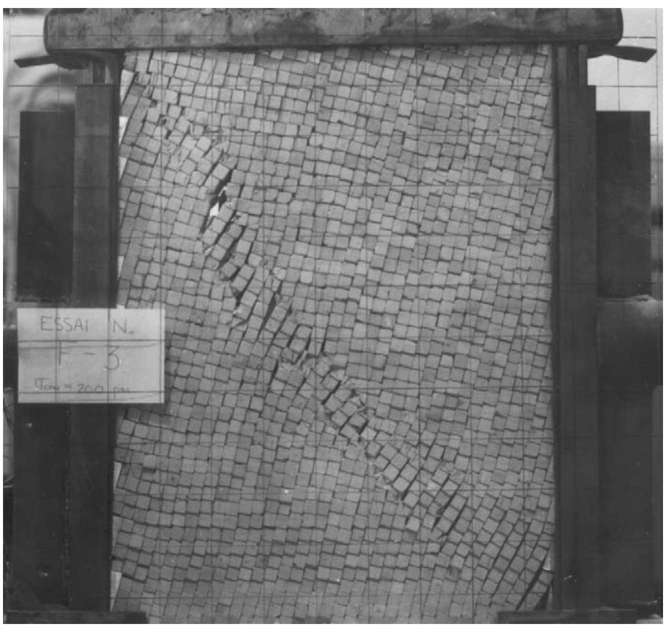


**Fig. 1.** Kink development in a biaxial test on small concrete rods [2].

Kink bands are assumed to be generated parallel to surfaces of high shear stress [11,14–16]. The positions and attitudes of KP are proposed to be determined with the first deformation at infinitesimal strain, depending of the authors, $\theta_{KP} = \pm 45^\circ$ [13,14] or $\theta_{KP} = \pm(45^\circ + \phi/2)$ [18] to the maximum principal stress (Fig. 2A). During deformation, $\theta_{KP}$ and $\alpha$ remain constant. With progressive deformation, the internal segments of constant geometry ($b$, $h$, $r$, $\varphi$) rotate from an initial angular position $\beta_0$ to a final angular position $\beta$ determined by the amount of rotation $\omega$ (Fig. 2B). The rotation is performed by layer-parallel passive slip and leads to an important dilatancy. The total volume variation, reflected by the width variation of the kink band, is composed of segment delamination and triangular openings at the hinges (Figs. 1 and 2). Rotation may continues until the delaminated segments return in contact one to the other in an orientation such that passive slip is no longer possible, restricted by a locking phenomenon. Further deformation of the rock mass is then accomplished by faulting along KPs [14]. Formation of KZI in both physical and numerical biaxial tests shows important similarities with the brittle rotational model of kink bands. In these tests (numerical and physical), rotation of segments of fixed length between KP of fixed orientation is observed, and important dilatancy occurs during deformation. For these reasons, the hinge-migration model has been rejected. However, the position and attitude of KP seems to be related to primary joints orientation, as presented and discussed later in this paper.

### 2.2. Stress–strain–dilatancy behaviour

A four-step stress–strain–dilatancy behaviour for kink banding was first proposed by Archambault and Ladanyi [19] (development zone, evolution zone, locking zone, and gliding zone), but in both physical and numerical simulations complete failure occurred before the locking zone so the two first steps were then sub-divided in five refined ones [9] (Fig. 3). The first step (A) is defined as "joints closure and elastic mobilization" because a linear increase in stress is associated with a negative dilatancy

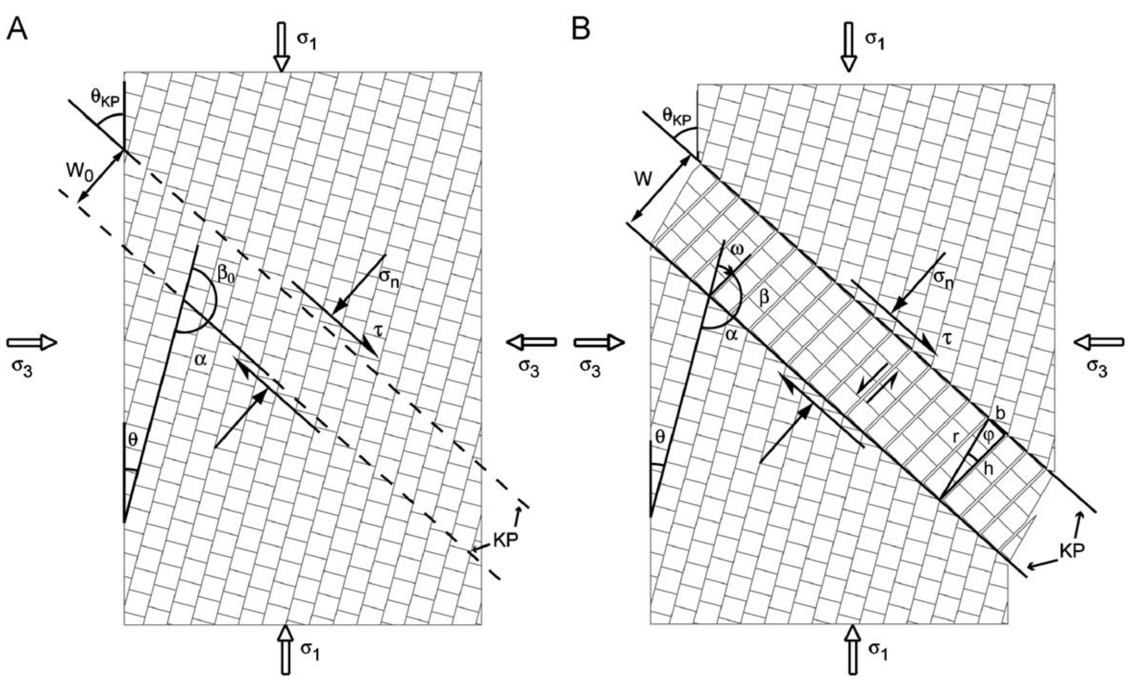


**Fig. 2.** Geometry of ideal kink band in jointed rock material. (a) KP's attitude determination. (b) After the internal segments rotation of $\omega$ degrees.