Bull Eng Geol Environ (2013) 72:509–522
DOI 10.1007/s10064-013-0514-3

ORIGINAL PAPER

# Assessment of corrective measures for alleviating slope instabilities in carbonatic Flysch formations: Alicante (SE of Spain) case study

**M. Cano · R. Tomás**

Received: 29 March 2013 / Accepted: 8 August 2013 / Published online: 16 November 2013

**Abstract** As is well known, in order to select remediation measures to correct or prevent slope instabilities, it is essential to identify and characterize the instability mechanisms. This task is especially complex for heterogeneous rock masses such as Flysch formations. This paper addresses the assessment of corrective measures used in carbonate Flysch formations by classifying and grouping field data reported in an available database in order to associate this data with various instability mechanisms and stratigraphic column types as well as with the corrective measures taken to stabilise them. For this purpose, 194 slopes have been geomechanically characterized, mainly by considering the observed instability mechanisms. The corrective measures that were applied have been evaluated for their suitability and performance, and, if applicable, the causes of their malfunction have been also studied. As a result, some guidelines based on the observed behaviour and the suitability of the correction measure as a function of instability type are proposed for similar slopes.

**Keywords** Flysch · Heterogeneous rock mass · Differential degradation · Erosion · Corrective measures · Slope instability

M. Cano (✉) · R. Tomás
Departamento de Ingeniería Civil, Escuela Politécnica Superior,
Universidad de Alicante, P.O. Box 99, 03080 Alicante, Spain
e-mail: miguel.cano@ua.es

R. Tomás
e-mail: roberto.tomas@ua.es

M. Cano · R. Tomás
Unidad Asociada de Investigación de movimientos del terreno
mediante interferometría radar (UNIRAD), UA-IGME,
Alicante, Spain

**Résumé** Comme il est bien connu, dans le but de sélectionner les mesures correctives pour corriger ou prévenir des instabilités de pente, il est essentiel d'identifier et de caractériser les mécanismes d'instabilité. Cette tâche est d'autant plus complexe pour les masses rocheuses hétérogènes telles que des formations de Flysch. Cet article traite de l'évaluation des mesures correctives utilisées dans les formations du Flysch carbonatée, en classant et groupement des données de terrain figurant dans une base de données disponible, afin d'associer ces données avec les différents mécanismes d'instabilité et les colonnes stratigraphiques type, ainsi que des mesures correctrices prises pour les stabiliser. A cet effet, 194 pentes ont été geomécaniquement caractérisées, principalement en examinant les mécanismes d'instabilité observées. Les mesures correctives qui ont été mis en œuvre ont été évaluées pour leur pertinence, la performance et, le cas échéant, les causes de leur dysfonctionnement. En conséquence, certaines lignes directrices fondées sur le comportement observé et l'adéquation de la mesure de correction en fonction du type de l'instabilité sont proposées pour des pentes similaires.

**Mots clés** Flysch · Masse rocheuse hétérogène · Dégradation différentielle · Érosion · Mesures correctives · Instabilité des pentes

## Introduction

The main aim of this paper, which is a companion to the description of instability mechanisms in Flysch rock masses by Cano and Tomás (2013), is to propose some corrective guidelines for remediation of instabilities in heterogeneous Flysch slopes. For this purpose, 194 slopes were examined and incorporated into a database in order to classify and group the data associated with various instability mechanisms and stratigraphic column types along with the appropriate corrective measures. This database has also been used in the evaluation of the effectiveness of these measures as a function of the type of instability mechanism. As a consequence, this work provides a valuable relationship between the instability mechanisms affecting the different types of Flysch stratigraphic column types and the corrective measure effectiveness. The rock exposures for this study belong to the Palaeogene series named *Surco Flysch El Campello-Villajoyosa* (Leret-Verdú et al. 1976 and Colodrón and Ruiz 1980). The study area extends along the Mediterranean coast of Spain over a densely populated region (over 200 inhabitants per square kilometer; IGN 2012), and is served by three main transportation routes (the AP-7 and N-332 highways as well as the Alicante-Denia railway) (Fig. 1). The area exhibits high formational and tectonic complexity as well as a variety of rock exposures, many of which are affected by instability mechanisms which are a hazard to both people and nearby infrastructures.

The transportation routes in the study area intersect the topography generating deep valleys and steep slopes. The instabilities affecting these slopes cause high annual maintenance costs. Furthermore, the coastline is dominated by the presence of high cliffs, many of which are densely urbanized on their crowns. These coastal cliffs are usually affected by instability processes which impose a significant hazard both to the infrastructure built along the crown of the cliff as well as users and infrastructure located at the cliff foot.

In order to select remediation measures to correct or prevent slope instabilities, it is essential to identify and characterize the instability mechanisms affecting the slope under study. This task becomes highly complex for heterogeneous rock masses such as Flysch formations. In this work, as previously mentioned, 194 slopes located in Flysch formations have been geomechanically characterized mainly by taking into account observed types of instability mechanisms. The relative arrangement of the associated lithologies, their competence and the geometrical relationship between slope and bedding allow the identification of the type of instability mechanism/s for each case (Cano and Tomás 2013). Note that competence here is evaluated from uniaxial intact rock strength, the internal structure and the observed in situ weathering behaviour of the structure. For this type of heterogeneous slope, the occurrence of instabilities associated with differential degradation processes is very common. However, the failure mechanisms related with differential degradation and/or erosion phenomena are usually not taken into account in transportation projects, perhaps because they are not considered relevant. These instabilities represent significant maintenance investments over the lifetime of the road (e.g., ditch cleaning, slope scaling, resloping, rock removal) and present road safety hazards. The instabilities may even trigger the failure of the slope, either in a gradual or sudden manner. Note that these degradation processes can be considered as triggering factors of new instabilities or failure modes per se.

Inventoried instability mechanisms are diverse and have been classified into six different groups (Cano and Tomás 2013): rockfall (Type RF), planar slide (Type PS), toppling failure (Type TF), buckling failure (Type BF), rotational slide (Type RS) and raveling and erosion (Type RE). Once the instability mechanism is identified and characterized

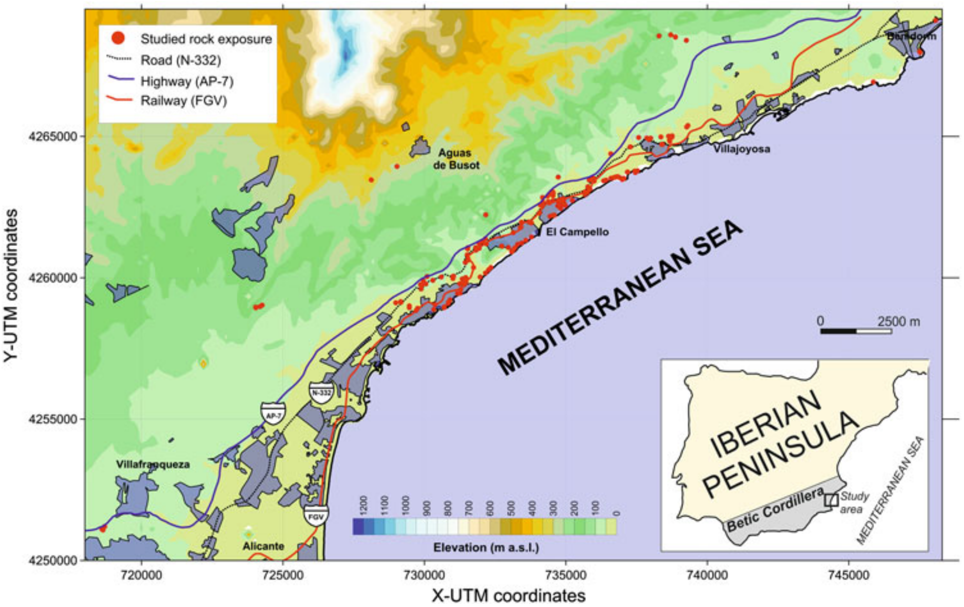


**Fig. 1** Map showing the study area and the characterized rock slopes

with previously described geomechanical criteria, preventive or corrective action may be taken. Corrective methods have been inventoried and their suitability, performance, and the causes of their malfunctions, where they have occurred, have been evaluated. This collected information permits the proposition of corrective guidelines for remediation of heterogeneous Flysch slopes which may possibly be extrapolated to other similar heterogeneous formations.

## Rock slope stabilization measures: state of the art

Rock slope corrective measures have been extensively studied by various authors (e.g., Fookes and Sweeney 1976; Hutchinson 1977 (slopes in general); Kengel 1978; Hoek and Bray 1981; Pierson et al. 1990; Romana 1992; Popescu 2001; Wyllie and Mah 2004; Andrew et al. 2011). In this section we present an overview of the most common slope corrective measures for generic rocky slopes, without considering the special characteristics of Flysch formations. The bibliography concerning Flysch formations is not extensive (e.g., Šestanovic et al. 1994; Uribe-Etxebarria et al. 2005; Arbanas et al. 2007, 2008). The application of the total engineering geology approach to the investigation, design, construction and operation of linear works (Baynes et al. 2005) is also of interest.

Normally slope corrective measures are divided into stabilization and protection measures (Wyllie and Mah 2004). Stabilization measures are active, acting on the cause of the instability in order to prevent its growth. Protection measures are passive and they aim to minimize the possible damage to people, goods and services when an instability process develops. Figure 2 shows a compilation of the 26 most common corrective measures divided by category.

Stabilization measures are classified into three main groups: modification of the slope geometry, internal reinforcement and external reinforcement.

A slope may be modified by resloping, used to modify the geometry of the slope, as well as trim blasting, bulk excavation, and finally, scaling, which may be manual or mechanical.

Internal reinforcement aims to increase rock mass and joint shear strength. This category includes rock bolts, dowels, shear keys (micropiles or rock bolts), rock anchors (tensioned or untensioned), and wire rope nets (which can be combined with a mesh net, a doweled mesh net, or a tied-back wall and beams). Highly-fractured rock mass global strength may be increased by means of rock mass bonding and, finally, reduction of pore pressure by means of drainage systems.

External stabilization systems mainly increase the rock mass resistance to weathering and superficial erosion while at the same time avoiding occurrence-associated instabilities such as rockfalls caused by sapping. Among the measures worth mentioning are shotcrete, which can adopt textures and colours to integrate the slope into the environment. Shotcrete can be applied without reinforcement for limited use to protect against weathering, or, if reinforced with steel fibres or welded wire mesh, for structural strengthening. It is important to note that shotcrete systems are highly vulnerable to water pressure, so it is necessary to design an appropriate drainage system. Other external stabilization measures consist of buttress support of solid rock blocks placed over degradable strata. Buttress support can be made of masonry, concrete, reinforced concrete, or shotcrete. One singular buttress support system is the *dentition* system, which consists of first scaling of soft and weathered material in the rock, the placement of a filter material in the resulting cavity together with a drainage system, and then protection against weathering and raveling by means of masonry, concrete or shotcrete. In soft rock slopes, protection from erosion commonly includes crown slope ditches, slope redesign by means of benches or the placement of a superficial vegetal cover. Gravity retaining walls and anchored walls that prevent instabilities such as planar slides are also considered to be external reinforcement measures.

Protection measures include warning signs, barriers and protective structures. Warning fences, which impede access to dangerous areas, block catch ditches placed on the foot of the slopes, and hanging net mesh (drapery systems), anchored on the crown of the slopes in order to drive small rock fragments towards the slope base, are also included in this category. Protective structures consists of tunnels or rock sheds (made of reinforced concrete or wire rope mesh) whose function is to avoid the disruption of normal activity in the protected area by fallen rock blocks. Other protective barriers are diaphragms which can be dynamic (rock catch fences) or static (barriers) depending on their function. Dynamic barriers (rock catch fences), which dissipate the energy of rock block impacts through self-deformation, can be flexible barriers or attenuators, which combine the benefits of a standard barrier with the benefits of a hanging net mesh. Static barriers do not deform during rock impact and, as a consequence, they must be very rigid. Some types of static barriers are: earthen barriers, concrete barriers designed for absorbing small impacts or structural walls, which can be made of reinforced concrete, metal structures or composite structures.

Corrective measures may also be classified according to work phase. During the planning, project and construction stages, adopted measures can be considered as preventive. However, during the lifetime of the adopted measures or after an instability event, they can be reclassified as

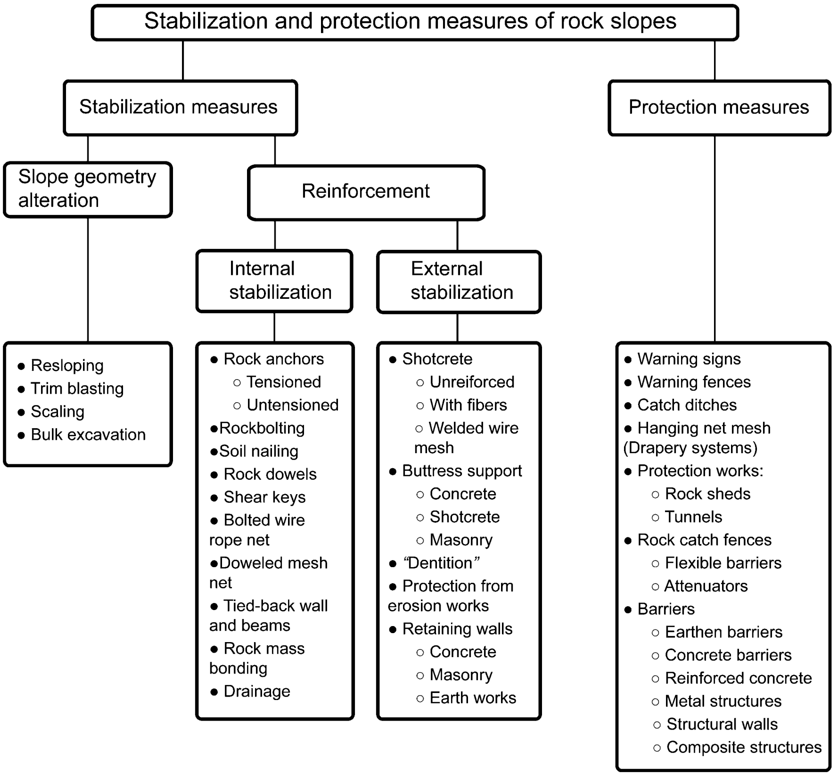


**Fig. 2** Compilation of common corrective measures of rock slope instabilities

corrective. Most of the preventive measures consist of the implementation of stabilization and protective systems. However, during the planning stages or even during early project stages measures to remediate the development of slope instabilities may be adopted at null or low cost.

## Lithological setting of the study area

The Flysch sequence of Alicante corresponds to sediments of pelagic domain predominated by sequences of grey marls and thin marly whitish limestones (hemipelagites) with a clear predominance of the marls.

The hemipelagic series, which represent the *background,* is completed by thick bedding calcarenites, thin bedding calcarenites, thick calcarenites with pillowed sedimentary structure (*pillow-beds*) (Roep and Everts 1992) and chaotic calcareous deposits formed by debrite and *mélanges* intercalations (Cano and Tomás 2013).

From a geomechanical point of view, the various Flysch lithologies are classified according to their competence, a common term used in engineering and in this work. A competence scale has been established considering three properties: the uniaxial compressive strength of intact rock, the internal structure of the set which forms each lithology and the weathering behaviour of the lithology.

Note that for the studied rock exposures there is a significant difference in competence between the marly and calcareous lithologies. This fact, together with the relative placement of the different lithologies is a determining factor in the observed instabilities (Cano and Tomás 2013).

In this work, thick bedding calcarenites and pillow beds are assumed to be of very high competence, thin bedding calcarenites of high competence, chaotic deposits (calcareous *mélanges* and debrites) of medium competence, marly limestones of moderate competence, H-marls of low competence and L-marls of very low competence.

The stratigraphic columns of the studied coastal slopes and cliffs are very complex due to the high number of lithological combinations of diverse and highly variable competence from which they are composed. However, it is very important to introduce a classification, since depending on the type of stratigraphic column, and on some geometric conditions that we address later in this article, certain slope instabilities may break loose. Examining a generic Flysch stratigraphic column typical of Alicante (Fig. 3), nine stratigraphic column "types" may be defined. These are typically found in short to medium-height slopes. The complexity of the stratigraphic column generally increases with increasing height. In the case of slopes formed by very complex stratigraphic columns that are made of a number of stratigraphic column "types", the instabilities associated with the complex stratigraphic column is the sum of the instabilities associated with each simple stratigraphic column type.

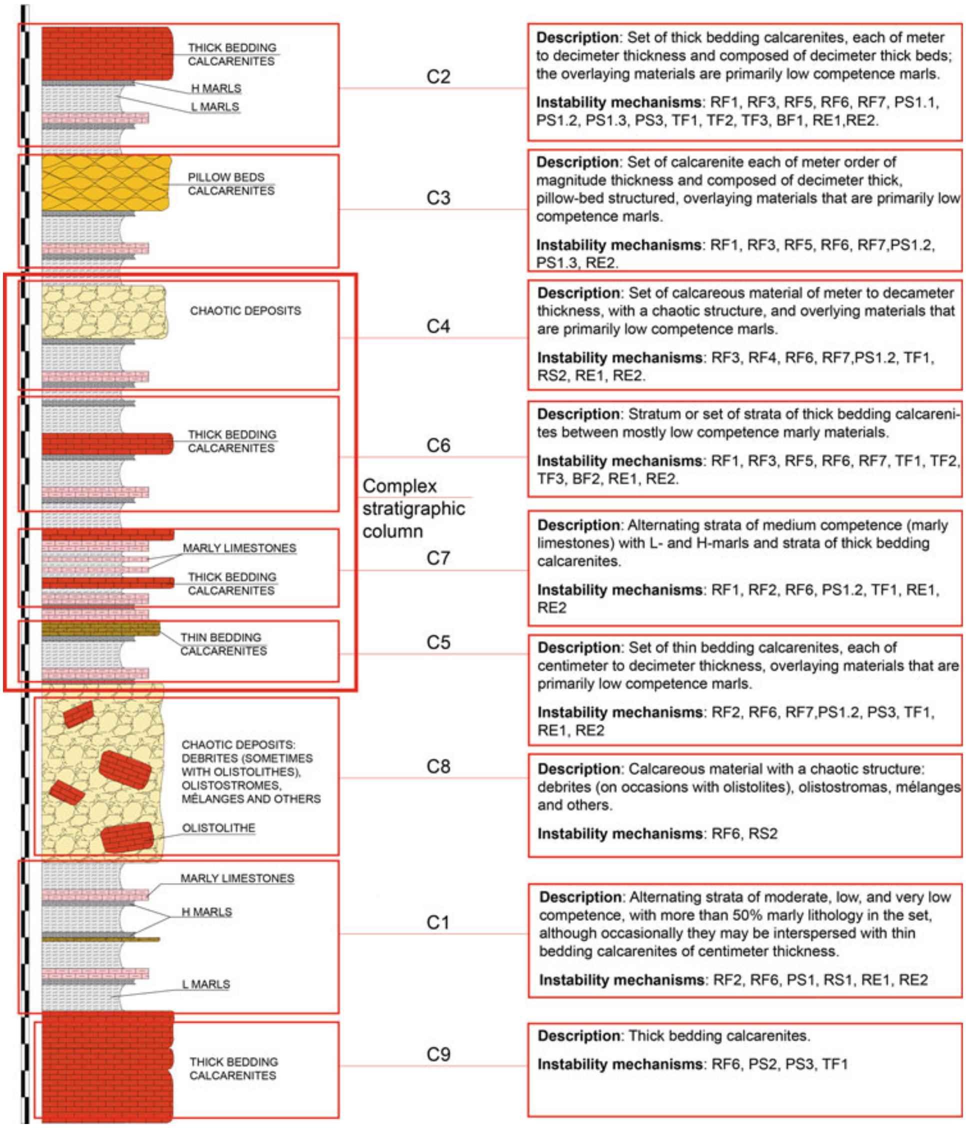
The classification of stratigraphic column types, with reference to the criterion regarding observed instabilities, is shown in Fig. 3.

In order to fully understand the geomechanical behaviour of these rock masses, it is important to note that the strata that compose them may be greatly fractured. The fractures represent one of at least two families of discontinuities that, together with stratification, cause the rock mass to break into parallelepiped blocks. The stratification set of discontinuities principally governs the observed mechanisms of rock fracture.

A detailed description of the lithological setting and the various pattern columns may be consulted in Cano and Tomás (2013). The summary in this section is included for the sake of completeness.

## Description and characterization of instability mechanisms

As previously mentioned, in order to recommend *ad hoc* corrective measures, it is necessary to first identify and characterize the previously described instability mechanisms. The failure mechanisms have been divided into six main groups: rockfall (RF), planar slide (PS), toppling failure (TF), buckling failure (BF), rotational slide (RS) and ravelling and erosion (RE). A summarized characterization of the instability mechanisms affecting the Flysch formation in Alicante is shown in Table 1. A detailed description of the instability mechanisms affecting Flysch rock masses in general can be found in Cano and Tomás (2013).



**Description**: Set of thick bedding calcarenites, each of meter to decimeter thickness and composed of decimeter thick beds; the overlaying materials are primarily low competence marls.

**Instability mechanisms**: RF1, RF3, RF5, RF6, RF7, PS1.1, PS1.2, PS1.3, PS3, TF1, TF2, TF3, BF1, RE1,RE2.

**Description**: Set of calcarenite each of meter order of magnitude thickness and composed of decimeter thick, pillow-bed structured, overlaying materials that are primarily low competence marls.

**Instability mechanisms**: RF1, RF3, RF5, RF6, RF7,PS1.2, PS1.3, RE2.

**Description**: Set of calcareous material of meter to decameter thickness, with a chaotic structure, and overlying materials that are primarily low competence marls.

**Instability mechanisms**: RF3, RF4, RF6, RF7,PS1.2, TF1, RS2, RE1, RE2.

**Description**: Stratum or set of strata of thick bedding calcarenites between mostly low competence marly materials.

**Instability mechanisms**: RF1, RF3, RF5, RF6, RF7, TF1, TF2, TF3, BF2, RE1, RE2.

**Description**: Alternating strata of medium competence (marly limestones) with L- and H-marls and strata of thick bedding calcarenites.

**Instability mechanisms**: RF1, RF2, RF6, PS1.2, TF1, RE1, RE2

**Description**: Set of thin bedding calcarenites, each of centimeter to decimeter thickness, overlaying materials that are primarily low competence marls.

**Instability mechanisms**: RF2, RF6, RF7,PS1.2, PS3, TF1, RE1, RE2

**Description**: Calcareous material with a chaotic structure: debrites (on occasions with olistolites), olistostromas, mélanges and others.

**Instability mechanisms**: RF6, RS2

**Description**: Alternating strata of moderate, low, and very low competence, with more than 50% marly lithology in the set, although occasionally they may be interspersed with thin bedding calcarenites of centimeter thickness.

**Instability mechanisms**: RF2, RF6, PS1, RS1, RE1, RE2

**Description**: Thick bedding calcarenites.

**Instability mechanisms**: RF6, PS2, PS3, TF1

**Fig. 3** Generic stratigraphic column of carbonatic Flysch of Alicante and description of the associated instability mechanisms. Note that the generic column is composed of simpler pattern columns. Pattern column descriptions are modified from Cano and Tomás (2013). *Scale bar* is in meters

**Table 1** Summarized characterization of the instability mechanisms observed in the study area (modified from Cano and Tomás 2013)

| Instability mechanism | Related stratigrapic column types (Fig. 3) | Description |
|---|---|---|
| Rockfalls | | |
| Rockfall with sapping | | |
| RF1. Rockfall of big blocks of bedding | C2, C3, C6, C7 | Occur on slopes where thick beds of calcarenites overlie weatherable rock. Blocks on the decimeter to meter scale fall by the roadside or on the road pavement, incurring a considerable maintenance effort on lines of transport |
| RF2. Rockfall of little blocks of bedding | C1, C5, C7 | Occur on slopes consisting of thin beds of calcarenites and other competent, millimeter to centimeter scale thick, strata that overlie alterable lithologies |
| RF3. Rockfall of big blocks (set) of chaotic deposits or set of thick bedding limestones | C2, C3, C4, C6 | Occur on cut-slopes or coastal cliffs of sufficient height to be formed by chaotic deposit sets or sets of thick bedding calcarenites overlying sets of weatherable lithologies, which apart from heavy maintenance may generate traffic accidents on byways |
| RF4. Rockfall of little blocks of chaotic deposits | C4 | Occur in conditions similar to the RF3 case, but due to the high density of joints in this type of lithology, blocks of decimeter scale are released, which tend to build up in the gutters and on the sides of highways |
| RF5. Lateral rockfal | C2, C3, C6 | The blocks do not fall in front of the slope, but rather laterally, into the trough of the slope |
| Rockfall of other origin | | |
| RF6. Rockfall without sapping | C1, C2, C3, C4, C5, C6, C7, C8, C9 | Involves fresh detachment of rocky material caused by a tension crack. The detached blocks are usually not large (centimeter to decimeter scale) and they accumulate by the roadside |
| RF7. Large (massive) rockfall | C2, C3, C4, C5, C6 | Affects a large mass of the slope caused by a plane of discontinuity that is not aligned with the stratification. This type of failure has road security implications and consequences much graver than the other types of rockfall |
| Planar slide | | |
| Slide over marls | | |
| PS1.1. Planar slide of isolated blocks | C2 | Slides consisting of meter-scale blocks of competent lithology on top of marly materials |
| PS1.2. Planar slides of stratified set of alternating series | C1, C2, C3, C4, C5, C7 | Concerns massive rockslides, with the moving mass of rock composed of alternating competent and marly materials placed over a marly stratum |
| PS1.3. Evolutive planar rockslide | C2, C3 | This rockslide consisting of competent lithologies over marls, occurs after an increase in the gradient of the underlying rock, which has deteriorated and moved under the influence of external agents (e.g., coastal erosion) |
| Slide over any rock types | | |
| PS2. Planar slide on calcareous rock | C9 | Slide that occur when strata of calcareous lithologies are parallel to the slope |
| PS3. Planar failure with lateral turn | C2, C5, C9 | Is a variant of the PS2 type mechanism where the movement of the block is impeded in the direction of the slope dip, causing a rotation of the block in the plane of the rockslide |
| Toppling failures | | |
| TF1. Toppling forwards the slope face | C2, C4, C5, C6, C7, C9 | The direction of movement is toward the free slope face |
| TF2. Lateral toppling | C2, C6 | These type of failures are produced in slopes where the estrafication is near vertical and oblique to the slope, with competent lithologies interlaid with alterable and moveable lithologies |
| TF3. Backtoppling | C2, C6 | Backtoppling develops in kinematic conditions in rockslides, when the underlying marly lithologies are removed and the competent layers pivot around the slope |

**Table 1** continued

| Instability mechanism | Related stratigrapic column types (Fig. 3) | Description |
|---|---|---|
| Buckling failures | | |
| BF1. Three hinge buckling | C2 | Occurs in situations where the stratification and the slope are parallel, the slope is close to being vertical, and calcareous materials overlie marls |
| BF2. Buckling like Grecian column | C6 | Occurs where the stratification and the slope meet obliquely with a near vertical dip. In this case, when weathering acts on the marly materials, the calcareous stratum or strata becomes isolated, without any lateral contact and a buckling fault occurs, similar to that of a block wall subject to its own weight |
| Rotational slide | | |
| RS1. Soil-type slumping | C1 | Slab-type rotational slides, occur in slopes that are made up primarily of marly lithologies |
| RS2. Rock slumping | C4, C8 | Occurs in slopes formed by rocks that have a chaotic structure with a multitude of erratic joints. This results in the release of blocks of varied forms and sizes |
| Ravelling and erosion | | |
| RE1. Raveling | C1, C2, C4, C5, C6, C7 | Gradual erosion, particle by particle or block by block of weatherable lithologies, that leave deposits at the foot of the slope. Occurs in outcrops where competent materials alternate with marly rocks where the strata and the slope meet obliquely and the strata are vertical |
| RE2. Raveling and erosion | C1, C2, C3, C4, C5, C6, C7 | Slopes with alternate lithologies in which slope and bedding are sub-parallel suffer from raveling and erosion (Type RE2), and surface runoff from these slopes may even cause gullies |

## Assessment of the effectiveness of the observed corrective measures

Following a field study, we have been able to identify and evaluate the efficacy of the corrective measures, as well as the stabilizing and protective procedures used to control the various instabilities in the carbonatic Flysch formation of Alicante (Table 2; Fig. 4). Using the elected criterion of this work for evaluation, stabilizing methods performed better than protective measures, especially stabilizing methods designed to avoid slope degradation that also take into account their integration into the environment. Effectiveness was assigned one of five grades, very high (5), high (4), medium (3), low (2) and very low (1) (Table 2).

## Results: analysis of proposed corrective measures

From the analysis based on observations of the corrective measures and given the peculiarities associated with carbonate Flysch formations, we rate the effectiveness of stabilizing measures higher than protective measures. Although stabilizing measures require a higher initial investment, they prevent slope degradation and, in the long run, represent significant savings in maintenance. We also consider it important to make decisions that tend to avoid slope instabilities in the planning stages of the project so that they do not develop later on.

Due to the extreme complexity of the rock exposures, it is very likely that on any slope the instability mechanisms are various and for this reason the corrective measures should take into account all possible instabilities. After performing a simple statistical analysis on the observed instabilities of 194 slopes, instability mechanisms have been associated with each type of stratigraphic column lithology (Fig. 3). The instability mechanisms develop as a function of geometrical relationships between the stratification and the slope (Cano and Tomás 2013).

In a slope formed by stratigraphic column type 1 (C1), the most adequate stabilizing method will be that which helps avoid slope degradation and it should be applicable to the entire slope surface. Among the possible methods, control of surface erosion (correct slope geometry, replanting with native species, etc.), and shotcrete, applied with a design for adequate drainage and with a colour that blends in with the surrounding scenery are possible choices. These techniques should be combined with other methods if geometric conditions are such that planar (PS1.2) or rotational (RS1) slides may develop. In these cases, internal reinforcement measures should be taken or the slope geometry should be modified.

If the slope is formed by a type 2 or 3 stratigraphic column (C2 or C3), rockfalls that originate with sapping of strata (with thickness on the order of meters) or sets of these strata (RF1, RF3, and RF5) may be stabilized by

**Table 2** Analysis of the corrective measures for Flysch formation instabilities in Alicante

| | Instability | Corrective measure | Effectiveness (From 1 to 5) | Evaluation |
|---|---|---|---|---|
| Rockfalls | Rockfall of big blocks of bedding (RF1) | Concrete buttress support | 4 | Controls the instability and works to limit slope degradation<br>This buttress may not blend in well with the environment |
| | | Catch ditches | 2 | May not always be effective as a protective measure<br>Does not prevent slope degradation |
| | | Bolted wire rope net | 2 | Does not controls the sapping<br>Does not prevent slope degradation |
| | Rockfall of little blocks of bedding. (RF2) | Catch ditches<br>Drapery systems<br>Catch ditches and drapery systems | 3 | Effective as protective measure<br>Do not prevent slope degradation |
| | Rockfall of big blocks (sets). (RF3) | Concrete buttress support | 4 | Controls the instability and helps prevent slope degradation<br>May not be visually pleasing |
| | | Masonry buttress support<br>Discontinuous masonry buttress support and intermediate shotcrete | 5 | Controls the instability and helps prevent slope degradation<br>Aesthetically pleasing |
| | | Catch ditches | 2 | Not always effective as a protective measure<br>Does not prevent degradation of the slope |
| | | Bolted wire rope net | 4 | Controls the instability<br>Does not prevent slope degradation<br>Blends well into the environment |
| | | Flexible barriers | No data | Does not prevent slope degradation |
| | | Barriers | 3 | Does not prevent slope degradation. Impacts by boulders or large rocks may damage the barrier |
| | | Catch ditches + barriers | 3 | Effective means of protection<br>Does not prevent slope degradation |
| | | Shotcrete protection | 2 | Should be used in combination with other techniques and needs to have adequate drainage |
| | | Structural shotcrete and bolting<br>Shotcrete protection on marl lithologies and hanging net mesh | 5 | Controls the instability and prevents slope degradation<br>Good visual integration with the surrounding environment (color and texture) |
| | | Bulk excavation | 3 | Does not prevent erosion of underlying degradable lithologies. Recurrence of the problem is possible |
| | Rockfall of heterometric and diverse morphology blocks (RF4) | Catch ditches<br>Catch ditches and drapery systems | 3 | Effective protective measure<br>Does not prevent slope degradation |
| | | Bolted wire rope net | 4 | Controls the instability<br>Does not prevent slope degradation<br>Good visual integration with the surrounding environment |
| | | Shotcrete protection | 3 | Should be combined with other measures |
| | | Barriers | 3 | Effective protective measure<br>Does not prevent slope degradation |
| | | Flexible barriers | No data | Does not prevent slope degradation |
| | Lateral rockfall (RF5) | Not observed | – | Does not prevent slope degradation |
| | Rockfall without sapping (RF6) | Catch ditches<br>Catch ditches and drapery systems | 3 | Effective protective measure<br>Does not counteract the cause of the slope instability |
| | | Doweled mesh net | 5 | For centimeter scale rockfalls, this method is highly effective |
| | | Protection Works (tunnel) | 4 | Very effective protective measure<br>Does not prevent slope instability |
| | Large (massive) rockfall (RF7) | Not observed at coastal cliffs<br>Catch ditches (undeveloped instability) | No data | The size of the potential massive rockfall is greater than the capacity of the catch ditch |

**Table 2** continued

| | Instability | Corrective measure | Effectiveness (From 1 to 5) | Evaluation |
|---|---|---|---|---|
| Planar slide | Planar slide of isolated blocks (PS1.1) | Not observed | – | Does not prevent slope instability or degradation of marl lithologies |
| | Planar slide of packed bedding on alternated series (PS1.2.) | Bolted wire rope net and mesh net | 3 | Effective stabilization measure for rockslides<br>Does not prevent slope degradation. May generate rockfalls and raveling |
| | | Structural walls | 4 | Effective stabilization measure for rockslides |
| | | Buttress support of competent strata | | Does not prevent slope erosion or raveling |
| | Evolutive planar slide (PS1.3.) | Not observed | – | Does not prevent the loss of rock mass along the face of the slope or lateral degradation |
| | Planar slide on calcareous rock (usual, PS2, or with lateral turn, PS3) | Doweled mesh net | 2 | A medium protective measure<br>Rock movement occurs inside the mesh (low density of dowels<br>The dowels are shorter than the thickness of the strata |
| Toppling | Toppling forwards the slope face (TF1.1 & 1.2) | Doweled mesh net | 1 | Dowels anchored in erodible marls<br>Dowels are shorter than the block size |
| | Lateral toppling (TF2) | Not observed | – | Does not prevent degradation of marly lithologies |
| | Backtoppling (TF3) | Not observed | – | Does not prevent degradation of marly lithologies |
| Buckling | Three hinge buckling (BF1) | Not observed | – | This instability has been observed in coastal cliffs |
| | Buckling like Grecian column (BF2) | Not observed | – | This instability has been observed in coastal cliffs |
| Rotational slide | Soil-type slumping (RS1) | Resloping | 4 | Effective stabilization measure<br>Does not prevent slope degradation or erosion of marly materials (principle material) |
| | | Shotcrete + rockbolting. Gunite color similar to the environment. | 5 | Controls the instability and prevents slope degradation<br>Good visual integration with the surrounding environment |
| | Rock slumping (RS2) | Earthen barriers | 2 | A rotational movement may reactivate instabilities in the upper part of the slope<br>May produce rockfalls without sapping |
| Ravelling and erosion | Raveling (RE1) | Protection works (tunnel) | 4 | Very effective protective measure<br>Does not prevent slope degradation |
| | | Doweled mesh net | 1 | Dowels are anchored in erodible marls<br>Material that breaks away accumulates in “bags” that may provoke mesh rupture<br>Dowel length is less than the breakaway blocks<br>Does not prevent slope degradation |
| | | Catch ditches | 2 | Very effective protective measure |
| | | Drapery systems | | Does not prevent slope degradation |
| | | Catch ditches and drapery systems | | |
| | Ravelling and erosion (RE2) | Drained shotcrete on mostly marly lithologies | 4 | Controls the instability<br>Adequate drainage system<br>Integration into the surrounding environment is less than optimal due to the shotcrete texture |

Effectiveness grade: (1) very low; (2) low; (3) medium; (4) high; (5) very high

preventing the underlying material from degrading by means of “dentition”, buttress support and shotcrete. Rockfalls of blocks from competent lithologies that occur without sapping can be overcome through the use of scaling, doweled mesh nets or bolted wire rope nets, depending on the magnitude of the problem.

As for massive rockfalls, it is necessary to excavate the part of the slope that is in danger of breaking free. The planar slides of type PS1.1 PS1.2 and PS3 should be repaired through methods using internal reinforcement (e.g., bolted wire rope net, rock anchors, shear keys) or external reinforcement (retaining structures and props). However, for the case of an evolutive planar slide (PS1.3), a partial degradation of the underlying marly materials occurs causing an increase in the dip of the slope so that calcenarite blocks slide. Thus, it is necessary for preventive measures to protect the slope from weathering through retaining structures, shotcrete, buttress support, and dentition and erosion protection in general.

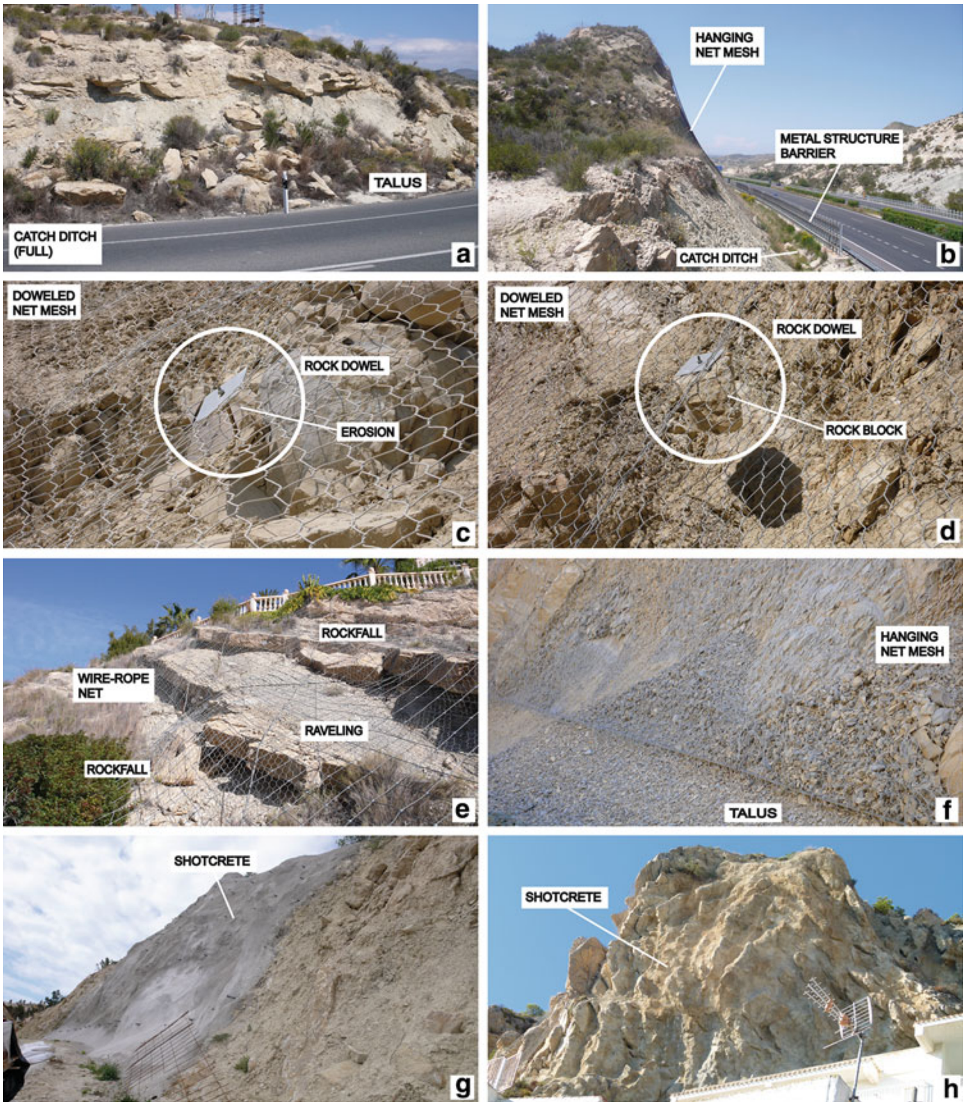


**Fig. 4** Examples of stabilization and protection measures used on carbonatic Flysch slopes. **a** Protection measures using catch ditches. Note that the slope is experiencing degradation and as a consequence the catch ditch is almost full. **b** Insufficient protection measures for an incipient instability (large rockfall). **c**, **d** Doweled mesh net. Low effectiveness stabilization measure. Note that the reinforcing dowel has been emplaced in a marly lithology which has suffered degradation and erosion, uncovering the dowel (**c**). Dowels shorter than the rock block thickness. The tension of the dowel causes the rock block to pull out of the slope (**d**). **e** Bolted wire-rope net. It stabilizes the slide, although the slope degrades and suffers rockfalls. **f** Hanging net mesh. The slope degrades, accumulating residual material at slope foot. **g** Reinforced shotcrete with drainage in marly lithologies. Note that the shotcrete integrates moderately well into the environment. **h** Shotcrete of chaotic structure lithologies; very well integrated into the environment (colour and texture). **i** Isolated concrete buttress support. The rest of the slope is exposed to weathering. **j** Masonry prop used for stabilizing a planar slide. **k** Composite structure barrier (reinforced concrete and metal structure) damaged after the impact of a chaotic material set rock block. **l** Various stabilization (discontinuous and stepped masonry buttress support) and protection (masonry catchment tank with a flexible barrier at the crown) measures. **m** Marly lithology slope foot stabilization with shotcrete, well integrated into the slope (colour and texture) and hanging net mesh in a chaotic deposit lithology. **n** Shotcreting and rockbolting of a predominantly marly slope (soil nailing). Soil-type slumping stabilization. **o** Tunnel protection against rockfalls, and erosion. **p** Retaining metal structure stabilizing a planar slide of strata placed over a marly lithology

Internal reinforcement methods are used to address usual toppling failure (TF1), such as rock anchors, rock bolts, etc. However, since lateral toppling failure (TF2) as well as backtoppling failure (TF3), are instabilities that develop due to degradation of low competence lithologies, the solution to these failures is the protection of these marly materials from weathering. The appropriate techniques run from well-drained shotcrete to erosion control. The three hinge buckling failure (BF1) may be addressed by internal stabilization methods, such as rock anchors, rock bolts, bolted wire rope net and rock dowels. Additionally, all of the methods adopted to avoid instabilities that are caused

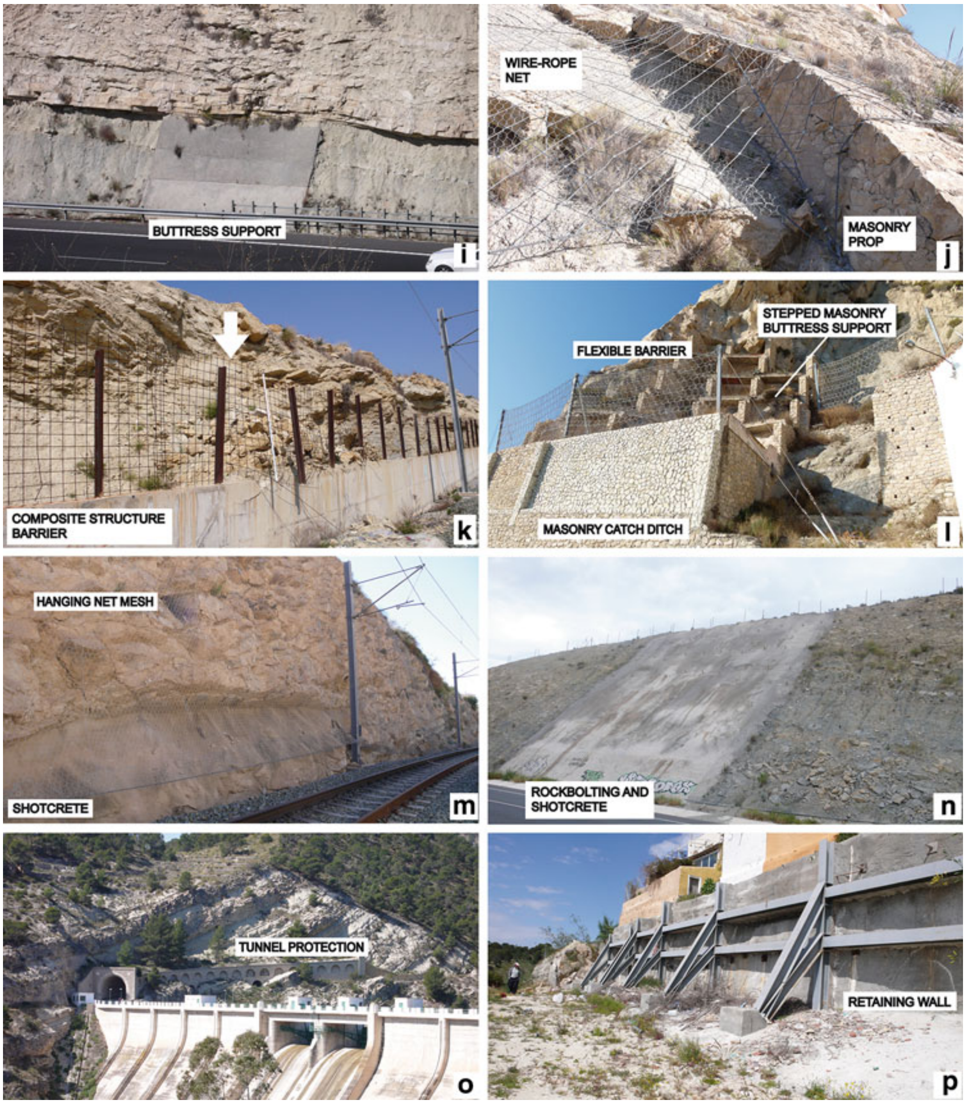


**Fig. 4** continued

by weathering and erosion processes also solve the raveling and erosion problem.

We next consider the case where the slope is a type 4 stratigraphic column (C4). For rockfall type instabilities, the required stabilization measures are similar to the previous cases, although here, we must also work on stabilizing the chaotic materials through internal reinforcement, such as rock mass bonding, doweled mesh nets, bolted wire rope nets, etc. With respect to other types of instabilities, these require treatments similar those mentioned for the previous columns.

For slopes corresponding to type 5 stratigraphic columns (C5), the most adequate stabilization is that of shotcreting the entire slope, including the layers that are competent in nature. With respect to other types of instabilities, these require treatments similar those mentioned for the previous columns. The shotcrete should be reinforced with fibre or welded wire mesh and effectively drained. This treatment prevents all associated instabilities for this slope type.

For slopes formed by stratigraphic column type 6 (C6) all instability mechanisms, except that of buckling failure (BF2), have the same solutions as those given for slopes formed by type 2 stratigraphic columns. For buckling, like the Grecian column instability mechanism, the more weather able lithologies have to be superficially protected in order to avoid the isolation of the competent vertical strata.

In the case where the slope is formed by type 7 stratigraphic columns (C7), the rockfalls due to sapping may be prevented by covering the entire slope with shotcrete and through the use of a masonry buttress or “dentition” to support the least competent strata. This last technique helps the slope to integrate into the environment, but is labour-consuming. Obviously, application of this technique eliminates problems of raveling and erosion. The other instabilities may be solved through internal reinforcement and through the use of retaining structures in the case of planar slides.

In Alicante Flysch, some slopes, including those of decameter height, are made up of materials that are exclusively calcareous, either with chaotic structure, like debrites (sometimes occurring with olistolites), olistostromas, mélanges and others (stratigraphic column type 8, C8), or in the form of thick bedding calcarenites (stratigraphic column type 9, C9). In the case of chaotic deposits, the observed instabilities are the RF6 type rockfalls and rotational slides of disintegrated rock (RS2). Both of these require internal reinforcement methods such as bolted wire rope nets, rock mass bonding, slope geometry alteration; etc., for stabilization. If, on the other hand, the formation consists of bedding calcarenites, the associated instabilities are RF6-type rockfalls, PS2 and PS3 type planar slides, and toppling failure (TF1), which also need internal stabilization methods.

As discussed, an increase in the height of the slope is generally accompanied by an increase in complexity. In these cases, one must analyze the types of stratigraphic columns that constitute the slope and apply the previously expounded methods over the entire height of the slope. Special attention needs to be given to application of the buttress support or “dentition” method, since these must be run from top to bottom and should cover all strata including the last competent stratum or set of strata.

One of the most cited stabilizing methods is shotcrete, which is applied according to local needs (without reinforcement, with steel fibre or with polymers or welded wire mesh). With the idea that the visual impact should be minimal, the mortar is dyed to blend in with the surroundings. Furthermore, in the case of complex slopes, where various sets of marly lithologies are treated, it is normally adequate to cover only those lithologies, without affecting the competent sets, although a certain amount of overlapping to insure weathering protection is useful.

In the case of shotcreteing an entire slope face or if most of the slope is marly, it is important to clean the head of the slope and to shotcrete it, at least as far as the length of the longest side of a competent block, or, if appropriate, to fill a discontinuity that could development into an instability. The drainage near the shotcreted zone must be adequate enough to ensure the complete drainage of water from the slope. If corrective measures are preventive, we need to act as soon as possible to prevent degradation of marly lithologies, even employing measures at the same time that the slope is excavated. This is especially important for L-marls which exhibit a very high weathering rate (weeks or even days) after excavation.

**Table 3** Recommended stabilization measures (in black) and protection measures (in grey)

| COLUMN | C1 | | | | | | C2-C3-C6 | | | | | C2 | C2-C3 | | C2 | C2-C6 | | | C2 | C2-C3-C6 | | C4 | | | | | | | | | C5 | | | | | | | | C6 | C7 | | | | | | | C8 | | C9 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Instability | RF2 | RF6 | PS1.2 | RS1 | RE1 | RE2 | RF1 | RF3 | RF5 | RF6 | RF7 | PS1.1 | PS1.2 | PS1.3 | PS3 | TF1 | TF2 | TF3 | BF1 | RE1 | RE2 | RF3 | RF4 | RF6 | RF7 | PS1.2 | TF1 | RS2 | RE1 | RE2 | RF2 | RF6 | RF7 | PS1.2 | PS3 | TF1 | RE1 | RE2 | BF2 | RF1 | RF2 | RF6 | PS1.2 | TF1 | RE1 | RE2 | RF6 | RS2 | RF6 | PS2 | PS3 | TF1 |
| Geometry alteration | ■ | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | | | | | | | | | | | | | | ■ | | | ■ | | | | | | | | | | | | | | | | | | | | ■ | | | | |
| Rock anchors | | | | | | | | | | | | ■ | ■ | | ■ | ■ | | | ■ | | | | | | | ■ | ■ | | | | | | | | | | | | | | | | ■ | ■ | | | | | | ■ | ■ | ■ |
| Rockbolting | | | ■ | ■ | | | | | | | | ■ | ■ | | ■ | ■ | | | ■ | | | | | | | ■ | ■ | ■ | | | | | | | | | | | | | | | ■ | ■ | | | | ■ | | ■ | ■ | ■ |
| Rock dowels | | | ■ | ■ | | | | | | | | ■ | ■ | | ■ | ■ | | | ■ | | | | | | | ■ | ■ | ■ | | | | | | | | | | | | | | | ■ | ■ | | | | ■ | | ■ | ■ | ■ |
| Shear keys | | | | | | | | | | | | ■ | ■ | | ■ | | | | | | | | | | | ■ | | | | | | | | | | | | | | | | | ■ | | | | | | | ■ | ■ | |
| Wire rope net | | | | | | | | | | ■ | | ■ | ■ | | | ■ | | | ■ | | | ■ | | ■ | | ■ | ■ | ■ | | | | | | | | | | | | | | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | | |
| Doweled mesh net | | | | | | | | | | ■ | | | | | | | | | | | | | ■ | ■ | | | | | | | | | | | | | | | | | | ■ | | | | | ■ | | | | | |
| Tied-back walls | | | | | | | | | | | | ■ | ■ | | | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | | | | | | ■ | | ■ |
| Rock mass bonding | | | | | | | | | | ■ | | | | | | | | | | | | | ■ | ■ | | | | | | | | | | | | | | | | | | | | | | | ■ | | | | | |
| Drainage | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | | | | | | | | ■ | ■ | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | ■ | | | | | |
| Shotcrete | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | | | | | ■ | | | ■ | ■ | | ■ | ■ | ■ | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | | | | | | |
| Buttress support | | | | | | | ■ | ■ | ■ | | | ■ | ■ | ■ | | | | | | | | ■ | | | | | | | | | | | | | | | | | | ■ | | | | | ■ | ■ | | | | | | |
| “Dentition” | | | | | | | ■ | ■ | ■ | | | | | | | | | | | | | ■ | | | | | | | | | | | | | | | | | | ■ | | | | | ■ | ■ | | | | | | |
| Erosion protection | ■ | ■ | | | ■ | ■ | | | | | | | | | | | ■ | ■ | | ■ | ■ | | | | | | | | ■ | ■ | | | | | | | | | ■ | | | | | | | | | | | | | |
| Retaining walls | | | | | | | | | | | | ■ | ■ | | | | | | | | | | | | | ■ | | | | | | | | | | | | | | | | | ■ | | | | | | | | | |
| Catch ditches | | | | | | | ▨ | ▨ | ▨ | ▨ | | | | | | | | | | | | | ▨ | ▨ | | | | | | | | | | | | | | | ▨ | ▨ | | ▨ | | | | | | | ▨ | | | |
| Drapery systems | | ▨ | | | | | | | | ▨ | | | | | | | | | | | | | ▨ | ▨ | | | ▨ | | | | | | | | | | | | | | | ▨ | | | | | | | | | | |
| Protection works | | | | | | | ▨ | ▨ | ▨ | ▨ | | | | | | | | | | | | | ▨ | ▨ | | | | | | | | | | | | | | | ▨ | ▨ | | ▨ | | | | | | | ▨ | | | |
| Rock catch fences | | | | | | | ▨ | ▨ | ▨ | ▨ | | | | | | | | | | | | | ▨ | ▨ | | | | | | | | | | | | | | | ▨ | ▨ | | ▨ | | | | | | | ▨ | | | |
| Barriers | | | | | | | ▨ | ▨ | ▨ | ▨ | | | | | | | | | | | | | ▨ | ▨ | | | | | | | | | | | | | | | ▨ | ▨ | | ▨ | | | | | | | ▨ | | | |

In Table 3, the corrective measures recommended in this work, along with the corresponding type of stratigraphic column making up each slope and its associated instabilities are summarized. The ideal stabilization measures, those previously mentioned as the most effective, are shown in black. In addition, recommendations of some protective measures are given in grey print., since in some cases it may not be possible to use the ideal measures, especially for very tall slopes.

## Conclusions

According to the inventory which we have completed, it is apparent that the corrective measures that have been implemented were developed to treat isolated instability mechanisms, principally rockfalls and planar slides. In the case of rockfalls, the adopted measures are, for the most part, protective measures (catch ditches, drapery systems and barriers in general). That is, the slope is allowed to degrade and the focus is on the protection of property and services.

However, in general, multiple mechanisms of instability within the same slope are not taken into account. In particular, neither instabilities caused by degradation/erosion processes, nor those of ravelling and erosion are considered as a failure mode, per se.

Also, we observed that integration of the applied method of remediation into the landscape was usually not a priority (i.e., no context sensitive design). However, the majority of the examined cases do not require a major financial expenditure to bring into enhanced performance condition.

After the evaluation of the examined stabilizing and protective methods, a series of measures have been proposed for Flysch formations, depending on the associated rock exposure lithologies and observed instabilities. Among the adopted methods, stabilizing methods are preferred over protective methods, the latter being recommended for cases where the former are not economically viable or are technically difficult to apply. Although the initial investment is more substantial, stabilizing methods are cost-effective in the long run since they significantly reduce maintenance costs and corrective intervention. When stabilizing methods are not adopted, the slope progressively degrades.

On the other hand, it is advisable to take preventive measures into account. Preventive measures will always minimize the development of instabilities and, although they are not strictly necessary, there is always the positive effect of taking into account possible instabilities and providing information about them up-front. This facilitates the application of eventual corrective measures. The application of corrective measures is more effective as more is known about the instability and its position on the slope face. Additionally, corrective measures are more effective if executed in the early stages of degradation and at specific locations. Among the preventive measures that stand out is the adaptation of the road routing to the stratification geometry. Finally, it is noteworthy that the performed observations and conclusions can be extrapolated to other study areas which present similar geological characteristics.

**Acknowledgments** The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve the quality of the paper. This work was partially funded by the University of Alicante under the vigrob-157, uausti11–11, and gre09–40 projects and by the Generalitat Valenciana under Project gv/2011/044.

## References

Andrew RD, Bartingale R, Hume H (2011) Context sensitive rock slope design solutions. U.S. Department of Transportation, Federal Highway Administration (FHWA), Central Federal Lands Highway Division, Publication No. FHWA-CFL/TD-11-002

Arbanas Ž, Grošić M, Jurić-Kaćunić D (2007) Experiences on flysch rock mass reinforcing in engineered slopes. In: 11th Cogress of the International Society for Rock Mechanics-Ribeiro e Sousa, Olalla & Grossmann (ed). Taylor & Francis Group, London 597–600

Arbanas Ž, Grošić M, Briški G (2008) Behaviour of Engineered Slopes in Flysch Rock Mass. Proceedings of the 1st Southern Hemisphere International Rock Mechanics Symposium, Perth, Australia, Australian Centre for Geomechanics 493–504

Baynes FJ, Fookes PG, Kennedy JF (2005) The total engineering geology approach applied to railways in the Pilbara, Western of Australia. Bull Eng Geol Environ 64:67–94

Cano M, Tomás R (2013) Characterization of the instability mechanisms affecting slopes on carbonatic Flysch: Alicante (SE Spain), case study. Eng Geol 156:68–91

Colodrón I, Ruiz V (1980) Mapa Geológico de Villajoyosa escala 1:50.000 (No. 847), IGME

Fookes PG, Sweeney M (1976) Stabilization and control of local rockfalls and degrading rock slopes. Quart J Eng Geol 9:37–55

Hoek E, Bray J (1981) Rock slope engineering, 3rd edn. Institute of Mining and Metallurgy, London

Hutchinson JN (1977) Assessment of the effectiveness of corrective measures in relation to geological conditions and types of slope movement. Bull Int Assoc Eng Geol 16:131–155

IGN, Instituto Geográfico Nacional (2012) Página web: www.ign.es

Kengel KJ (1978) Types of rockslopes_Possibilities of classification and rerivation of correctives measures. Bull Int Assoc Eng Geol 17:52–55

Leret-Verdú G, Núñez-Galiano A, Colodrón-Gómez I, Martínez del Olmo W (1976) Mapa Geológico de Alicante escala 1:50.000 (N 872) IGME

Pierson LA, Davis SA, Van Vickle R (1990) Rockfall hazard rating system implementation manual. Federal Highway Administration (FHWA). Report FHWA-OR—EG-90-01. FHWA, U.S. Department of Transportation

Popescu M (2001) A suggested method for reporting landslide remedial measures. Bull Eng Geol Environ 60:69–74

Roep TB, Everts AJ (1992) Pillow-beds: A new type of seismites? An example from an Oligocene turbidite fan complex, Alicante, Spain. Sedimentology 39:711–724

Šestanović S, Štambuk N, Samardžija I (1994) Control of the stability and protection of cut slopes in Flysch. Geol Croat 47(1):139–148

Uribe-Etxebarria G, Morales T, Uriarte JA, Ibarra V (2005) Rock cut stability assessment mountainous regions. Environ Geol 48:1002–1013

Wyllie DC, Mah CW (2004) Rock slope engineering, civil and mining, 4th ed., Spon Press, Taylor & Francis Group, New York, p 431