Analysis and Design of Cellular Sheet Pile Structures, Case Study: The Bahmanshir Upstream Cellular Dam

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Abstract

The construction of Bahmanshir upstream cellular dam location is on Bahmanshir river at 300 m downstream of its intersection with Karun river in southwest of Iran. Main project features are: Circular cellular dam in upstream of the Bahmanshir River, dam height 16m,free board 8m, Navigation Lock (25 m) and Movable bridge (2 Leaves).This project consists of circular dam with 8 cells, navigation channel, moveable bridge, and miter gate which all are unique in Iran. Main body of cellular dam is a sheet pile wall dam arranged circular and filled by selected coarse grain soil in lower parts and mass concrete at top areaIn this paper, applications and advantages of cellular structures is introduced. Also, various methods of analysis and design of cellular structures are investigated and related comments of several reliable standards and references are mentioned. In many cases especially in marine projects and complex geotechnical conditions, construction of cellular structures may be the optimum or probably the exclusive practical method. Nowadays sheet piles are common structures that are used in coastal projects. Successful experiences of design and construction of the cellular structures are available now in Khoozestan region, such as Bahmanshirupstream cellular dam which is in construction stage.

Keywords: Sheet Pile, Cellular, Cofferdam, Analysis, Bahmanshir

1. INTRODUCTION

For constructing dams, quay walls and other marine structures, in many cases, geotechnical seabed or riverbed subsurface condition, so position of fine/coarse grain borrow material is limited using of heavy gravity structures to apply intensive loads and forces to ground surface directly, due to rigidity of structure (e.g. concrete structures) or existence of large long term consolidation subsidence (e.g. earth structures). Thus, in these cases, using of the different types of cellular structures, which are shaped with various combinations of sheet piles, can be considered as a proper solution [1]. Cellular structures can be designed as self-supporting gravity walls not requiring any supplementary waling and anchoring. They can be founded directly on bedrock, without any embedment. They are economical solutions for works in deep waters, high retaining works and long structures.

Generally, applications of straight-web sheet piles fall into two categories: for temporary works and for permanent works. When used for temporary works, a series of individual sheet pile cells form massive cellular cofferdams enabling large and deep excavations to be carried out in the dry in or alongside riverbeds, etc., where the excavations often go down to bedrock.

For permanent structures, cellular sheet pile structures or cofferdams are used above all in the maritime-engineering sector, to build:

- Massive quay walls: the structure serves as a retaining wall and as a berth for ships;
- Piers and jetties which can be used to berth ships on both sides;
- Dolphins: works made up of a single cell, used for berthing or guidance of ships;
- Breakwaters: harbor-protection structures (berthing not usually possible).

It is less common for cells to be used on land, but they can be chosen for massive retaining structures, taking advantage of their weight to prevent slips.

It is worth to mention, successful experiences of design and construction of the cellular structures are available now in our country (Khoozestan province), such as Bahmanshir downstream cellular dam (in design & construction process), Bahmanshir upstream cellular dam (in construction process) and Mared and TorrehBokhah constructed pump stations.

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2. Technology and Construction Method

As mentioned, nowadays sheet piles are common structures that are used in coastal projects. Sheet pile diaphragm or cellular wall structures are used to form a water barrier and providing a dry work area. These cells are filled with soil. The primary advantages of circular cells are that each cell is independent of the adjacent cells, it can be filled as soon as constructed, and it is easier to form by means of templates. Also at the end of project these elements can be dismantled and used in another project.

2.1. Construction Method Statement

In construction of cellular structures, safety is a paramount concern, since workers and machinery will be exposed to the hazard of flooding and collapse. For a typical cellular structure, the construction procedure is as follow (Figure 1):

- Pre-dredge to remove soil or soft sediments and level the area of the structure
- Drive temporary support for sheet piles
- Set steel sheet piles using pre constructed template
- Drive sheet piles to required grade
- Excavate inside the grade or slightly below grade, while leaving the cofferdam full of water
- Place earth or rockfill material
- Dismantle the sheet pile template
- Construct new cell

It shall be noted that construction of each cell is done after completion of the previous cell.

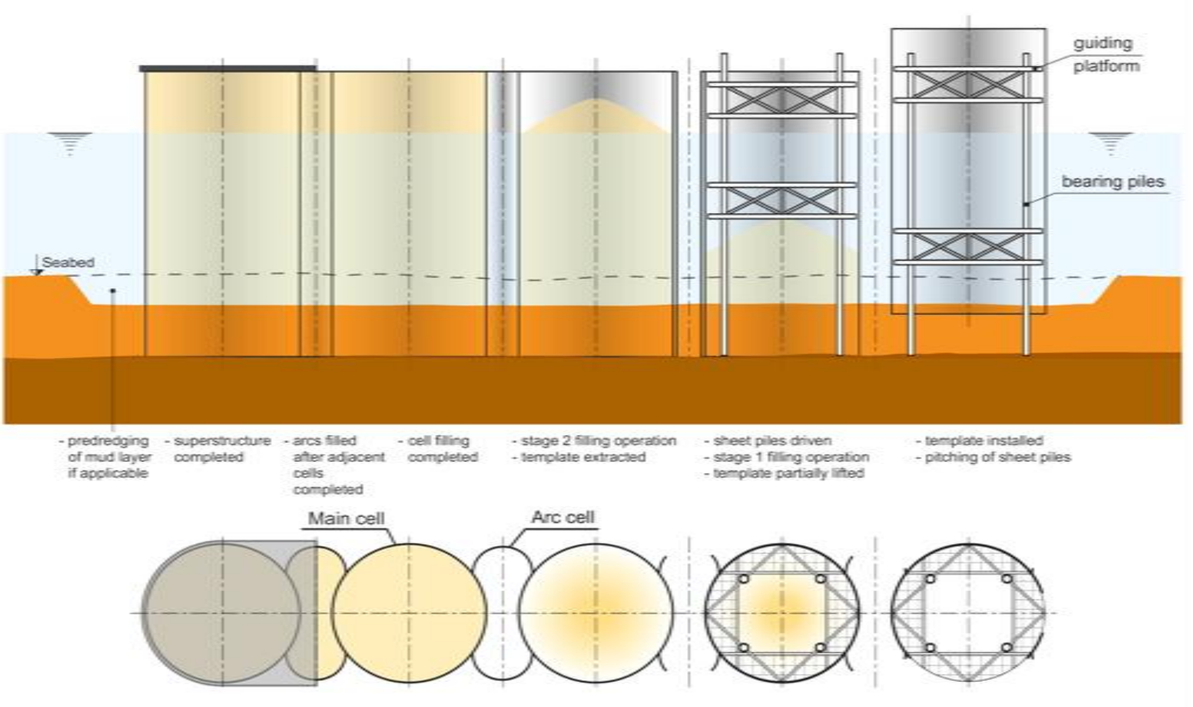

Figure 1. Installation phases of circular cell structures

2.2. CELLULAR CONFIGURATIONS AND DIMENSIONING

Cellular structures are a combination of earth and sheet piling. The cell shell and filling of the steel sheet pile act as an integrated structure that individually are unstable. It is recommended that the hollow space in the cells be filled to a sufficient density with sand or gravel of good quality. It is not desirable to use a clayey soil as the filling material. When clayey soil is to remain in the cells, it is necessary to make separate examination because the deformation of the cells may become significantly large. They depend for stability on the soil used to fill the cell and the steel sheetpiling. Either material used alone is unsatisfactory; both materials in combination provide a satisfactory means to develop a dry work area in water-covered sites such as ocean or lakefront or river area construction projects. It can resist large lateral loads, which may cause noticeable cell movement, and are generally installed where difficult site condition exist. Figure 2 shows most of the commonly used filled cellular configurations.

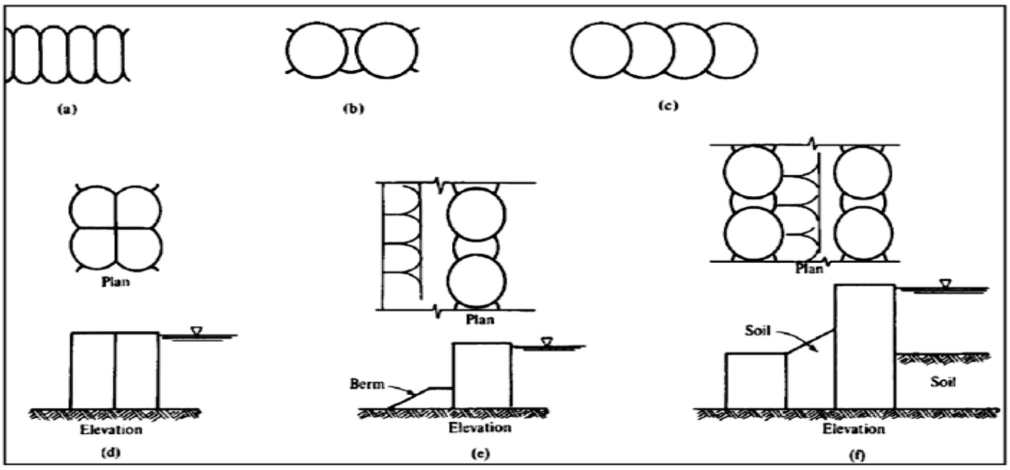

Figure 2. Cellular configurations used for most installations: (a) diaphragm, (b) circular, (c) semicircular, (d) cloverleaf, (e) circular with berm, (f) double circular cells

Cellular structures mainly are of three types: circular, diaphragm and cloverleaf. These structures are usually constructed of straight web sheetpiling since a cell full of soil and/or water tends to split so that tension stresses are produced in the web. Cellular structures are most commonly constructed using circullar cells with smaller connecting partial cells. Cells are constructed by assembling the necessary number of sheet piles around a few number of templates (usually in ring form) which are anchored in specified vertically spaces. Sheetpiling should be conducted in specific pattern and sequence to prevent distortion and skewing of sheet piles [2]. In Figure 3, construction of Bahmanshir upstream cellular dam, which has been built by Jyane Construction Co. and under supervision of MahabGhodss Consulting Engineering Co., is shown [3].

Figure 3. Construction of Bahmanshir upstream cellular dam in Khoozestan

Depending on the location and function of the cells, various data concerning the site and soil condition must be developed for a satisfactory installation. Also, the necessary information about the site would include the following:

- Low-and high-water elevations
- Cross section and ground line profiles
- Soil type and thickness
- Soil permeability and shear strength data

Generally, the ratio of average width to height of diagram and circular cells used in water-retaining cofferdams on rock is 0.85, although much lower ratios (less than 0.6) have been used successfully. The diameter of the cell is limited by the characteristic interlock resistance.

2.3. Environmental Conditions and Advantages of Cellular Structures

The cellular structures or open cells system performs very well in a variety of conditions (Figure 4):

- High loads
- Deep water
- Soft soils
- Minimal embedment
- Scour
- Ice
- Seismic conditions
- Long-term settlement

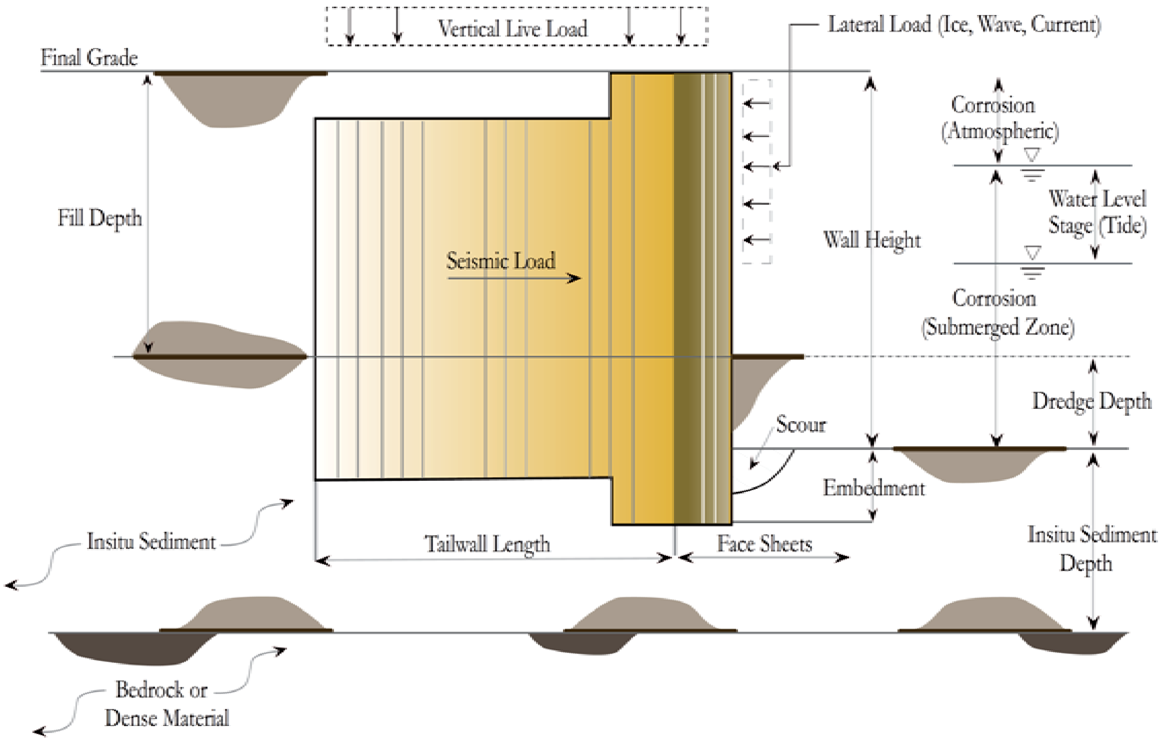

Figure 4. Environmental conditions and loading affected a cellular structure

Also, circular cells in the construction of cofferdams offer several advantages:

- Circular cells may be filled immediately after they have been built, regardless of the relative height of fill in adjacent cells.
- Filled cells can be used as the working platform for the installation of the new cells.

One of the many advantages of sheet piling is that it is impermeable to hazardous materials, so the possibility of seepage is limited to the interlock zone. Interlock sealing system is factory-fitted in the sheet piling interlocks. It comprises a machine profiled seal in the threading interlock and an injected seal adapted to the interlock slot in the pre-fabricated interlock. Therefore any seepage in sheet pile cell will be prevented.

3. ANALYSIS AND DESIGN PRINCIPLES

As shown in Figure 5, design of cellular structures requires providing an adequate margin of safety against the following [4]:

1. Excessive tilting or base rotation of cell
2. Stability of base and sliding
3. Interlock and connection failure (cell bursting)
4. Overturning

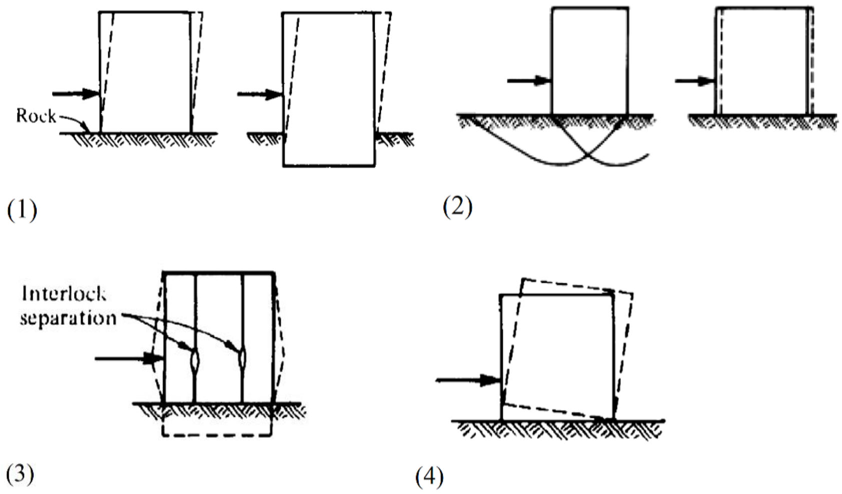

Figure 5.Failure modes of filled cells: (1) internal shear (tilting) (2) base failure and sliding (3) interlock separation (4) overturning

Interlock and connection failure or cell bursting is usually critical since the interlock is the weakest part of the system [6].

Due to fact that the using of sheet piles for construction of structures such as quay wall, cofferdam, etc. has been increased and large volume of materials usually use in projects, hence the resulting costs; any instability of structure can lead to large expenses. There are a wide variety of methods to design sheet piles. In all of these methods two main quantities which govern the design are critical penetration depth and maximum moment in sheet pile. The conventional design method of limit equilibrium has its known limitations in modeling of soil as rigid blocks sliding on predetermined surfaces and considering of sheet piles as rigid materials. On the other hand numerical methods can involve any material behavior for soil and also flexibility properties for sheet piles. Meanwhile, it is possible to obtain the resulting displacements of sheet piles from numerical analyses which can help engineer to evaluate the behavior of structure under various loading conditions [7].

3.1. DESIGN IMPORTANT PARAMETERS OF CIRCULAR CELLS

Cellular structures are made up of a series of relatively closely-spaced circular cells linked by connecting arcs. Each cell is self-supporting once it is filled. It is therefore independent of adjacent cells, which makes it easy to build this type of cofferdam in water. The most important parameters for circular cells are (Figure 6):

- Radius of the main cell (r_m)
- Radius of the connecting arcs (r_a)
- Angle between the main cell and the connecting arc (θ)
- System length (x)
- Positive or negative offset between the connecting arcs and the tangent planes of the main cells (d_y)
- Equivalent width (w_e)

The following relationships apply:

- The greater the angle (θ) between cell and arc, the greater the ratio of r_a/r_m. For $\theta = 90^{\circ}$ and $d_y = 0$: $r_m = r_a$.
- With constant r_m and increasing r_a, the system length (x) also increases and the equivalent width decreases, if $d_y = 0$.
- The governing circumferential tensile force increases as the r_a/r_m ratio increases.
- The developed pile wall surface per meter of cofferdam decreases as the r_a/r_m ratio increases.

- With respect to circumferential tensile force, the solution with the smallest possible angle θ is the optimum for a given equivalent width (w_e), but also the most unfavorable with respect to the quantities of material required.
- If the straight-web piles have any residual resistance to be mobilized, the optimum solution will have an angle between 30° and 45°. For design reasons (welding), this angle may not be less than θ = 30°.

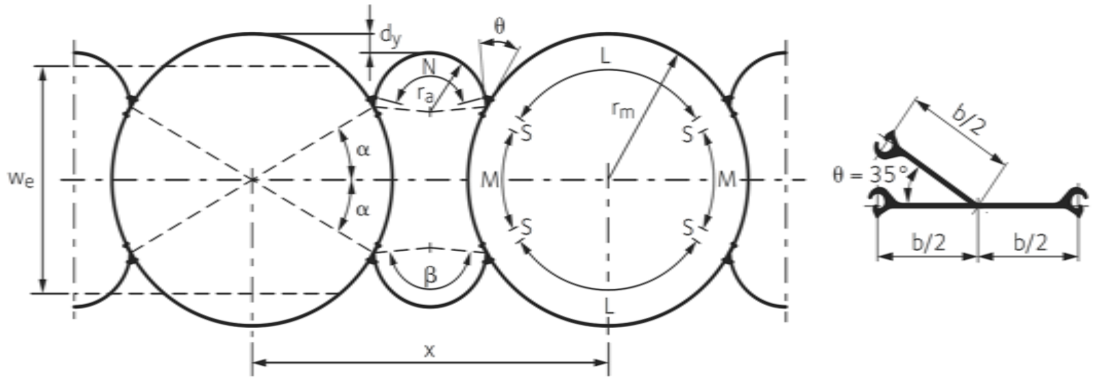

Figure 6.Geometrical values for circular cells

A cellular cofferdam is a flexible structure. After the closure of the cell structure and eventual filling, the cell will undergo horizontal movements of the piling ring at the top of the structure resulting in an increase of the cell diameter, as well as local deformations due to the barreling effect. This has to be taken into consideration while designing cellular constructions by assuming that the theoretically designed geometry of the cell will be slightly different from the geometry practically obtained on site.

3.2. Analyses Methods of Cellular Structures

There are no theoretical solutions for any of above mentioned factors owing to the complex interaction of the geometry, sheet piles and cell fill. As a consequence of these uncertainties, related analysis and design are semi empirical approaches. The main of these methods are as follows [5, 6]:

- TVA (also called Terzaghi's method)
- Cummings method
- Hansen's (or Danish) method
- Other methods (e.g. Kitajima, OCDI and etc.)

Of these the TVA (1966, but publication now out of print) and Cummings (1960) methods are commonly used in the United States and elsewhere. The Hansen method as modified by Ovesen (1962) is used much less—primarily in Europe. More cellular structures have been built by TVA and the U.S. Corps of Engineers than by any others. Thus, the TVA and Cummings methods have much to commend them since, if one must use empirical methods, the simpler ones are preferable. This is a major drawback of using the Hansen method—aside from there being less construction experience to validate it. Dismuke (1975) provides a summary of the several design methods in use in the United States, and Sorota and Kinner (1981) describe a recent use of the several U.S. design methods in a major cellular cofferdam installation. This latter reference provides instrumented data comparing design to the as-built stresses and deformations; particularly valuable since there is not a great deal of published post design verification available.

Detail of above mentioned methods to analysis of cellular structures are completely presented in related references (e.g. [1], [4], [5] & [6]), thus for brevity, it is not represented in this paper.

4. Bahmanshir Upstream Cellular Dam

Construction of Bahmanshir upstream cellular dam has been completed about 5 years ago. The construction location is on Bahmanshir river at 300 m downstream of its intersection with Karun river in southwest of Iran. The other accessories of this project such as navigation channel and moveable bridge are under construction now. As mentioned, arrangement of a cell by junction of sheet piles together and driving of them by hydraulic hammer is shown in Figure 3.

4.1. GENERAL PROJECT LAYOUT AND SPECIFICATION

In Figure 7, general layout of Bahmanshir upstream cellular dam is shown. This project consists of circular dam with 8 cells, navigation channel, moveable bridge, and miter gate which all are unique in Iran. Main body of cellular dam is a sheet pile wall dam arranged circular and filled by selected coarse grain soil in lower parts and mass concrete at top area. Construction of circular dam has been performed (by Jyane Construction Company under supervision of MahabGhodss Consulting Engineering) but some remedial activities includes interface of dam and other parts of the project shall be done according to the execution progress. Navigation channel is a concrete U type channel that is laid on several numbers of micro piles on the river bed. Construction of micro piles and U channel is under taking but some parts are hold due to finalizing design of gate and bridge.

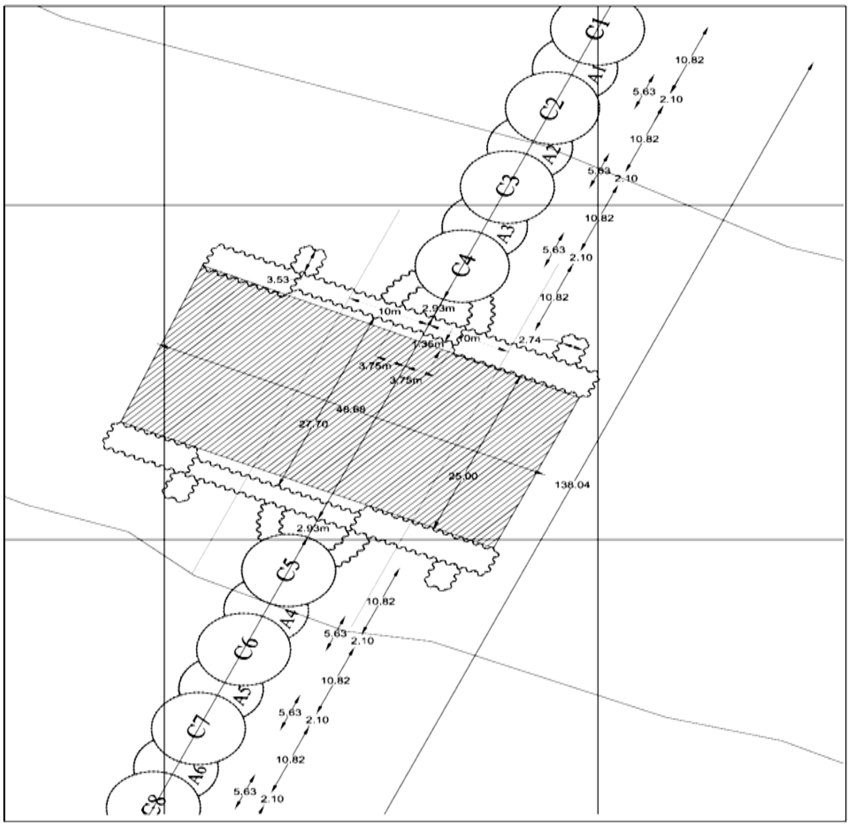

Figure 7.General layout of the Bahmanshir upstream cellular dam and other accessories

Dimensions of the above mentioned project in different parts is mentioned as follow [3]:

- Bahmanshir river width ≈ 75 m
- Clearance of navigation channel ≈ 25 m
- Total length of navigation channel ≈ 50 m
- Top elevation of navigation channel slab ≈ -5.0 m
- Top elevation of bridge ≈ +4.0 m

5. CONCLUSIONS

In this paper, applications and advantages of cellular structures is introduced. Also, various methods of analysis and design of cellular structures are investigated and related comments of several reliable standards and references are mentioned. In many cases especially in marine projects and complex geotechnical conditions, construction of cellular structures may be the optimum or probably the exclusive practical method. Nowadays sheet piles are common structures that are used in coastal projects. Successful experiences of design and construction of the cellular structures are available now in Khoozestan region, such as Bahmanshir downstream cellular dam which is in construction stage.

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