1

Introduction

1.1 Geological Characteristics of Unconsolidated Heavy Oil Sandstone Reservoirs

1.1.1 Distribution Characteristics of Unconsolidated Heavy Oil Sandstone Reservoirs

In 1992, Penbeyrt and Shaughnessy pointed out that 70 percent of the world’s oil and gas resources are present in poorly consolidated sandstone reservoirs. These unconsolidated pays are distributed in nearly every oilfield around the world, such as Wilmington Oilfield and Kern River Oilfield in California, Bell Creek Oilfield in Montana, and S.E. Pauls Valley Oilfield in Oklahoma. Oilfields such as Cold Lake, Elk Point, Lindbergh, Lloyminster, Frog Lake, and Cactus Lake in Canada and some Paleogene-Neogene reservoirs in Indonesia, Trinidad, and Venezuela belong to unconsolidated reservoirs. In China, unconsolidated reservoirs are distributed in almost all existing oilfield areas (except Sichuan Basin), such as Shengli Oilfield, Dagang Oilfield, Bohai Oilfield in Bohai Bay, Liaohe Oilfield in Songliao Basin, and Karamayi Oilfield in Junggar Basin.

One feature of these reservoirs is a shallow depth, usually less than 1800 m. The shallowest ones are outcropping or buried under surface of tens of meters or 100 m of Paleogene–Neogene pay. Outside China, unconsolidated reservoirs also exist, such as heavy oilfields in Alberta, Canada. From the view of the structure, poorly consolidated heavy oil reservoirs are mainly distributed in the shallow pay of the slight dipping slope of basin or depression, the edge of salient, upper part
of flat salient, or faulted anticlinal trap of depression. These reservoirs have rich faults and are dominated by anticlinal structure reservoirs or structural nose reservoirs (Table 1-1). Edge water or bottom water is formed in these unconsolidated reservoir (especially in oilfields outside China), and some of them have a gas cap. Due to the features of shallow depth and poor cementation, porosity of these pays is commonly greater than 25%. Most of the heavy oil reserves are in this kind of reservoirs, where temperature and pressure are commonly very low. For instance, about 88% of heavy oil reserves in the northwest edge of Junggar basin is buried less than 600 m, where the formation pressure is commonly between 1.8 and 4.0 MPa and the formation temperature is 16° to 27°C.

1.1.2 Sedimentary Characteristics of Unconsolidated Sandstone Reservoirs

Sedimentary types of unconsolidated sandstone reservoir vary, including many facies of marine sediment and continental sediment, and most of them are continental facies, marine–continental transitional facies, delta facies, fluvial facies, and alluvial facies of fluvialacustrine transitional facies. There are also fan delta facies.

Lithology is mainly poor sorting and rounding fine, medium, and coarse sandstone. The components of sand particles are mainly composed of quartz, feldspar, and clastic debris with high clay content (commonly 6% to 9%).

In the Clear Water zone of Burnt Lake area of Cold Lake Oilfield, the thickness of the pay is 20 to 30 m and lithology is fine sandstone. Components of particles are 20% quartz, 20% feldspar, 60% clastic debris, and clay content of 10% to 20% of the total rock volume, mainly consisting illite, chlorite, smectite, and kaolinite.

The second zone of Dongying group of SZ 36-1 Oilfield in Bohai Bay is a set of delta front subfacies of near shore lacustrine facies, including under-water distributary channel, mouth bar, interdistributary area, distal bar, sheet sand, sedimentary microfacies, and meare subfacies. The properties of crude oil in the oilfield are high density, high viscosity, high content of colloid and asphaltene, low content of sulfur and wax, and low pouring point. The reservoir of SZ 36-1 is obviously a heavy oil reservoir.

1.1.3 Diagenetic Features of Unconsolidated Sandstone Reservoirs

Diagenesis refers to the physical and chemical functions when the deposits change to sedimentary rock and before the metamorphic process. Because the unconsolidated sandstone reservoir buries shallow, they generally experience compaction
### Table 1-1  Sedimentary Facies and Tectonic Features of Typical Unconsolidated Sandstone Heavy Oil Reservoirs

<table>
<thead>
<tr>
<th>Oilfield</th>
<th>Formation</th>
<th>Sedimentary Facies</th>
<th>Structural Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jinglou Oilfield</td>
<td>Sublayer III of Hetaoyuan Formation, Paleogene</td>
<td>Fan Delta</td>
<td>Anticline with complicated faults, asymmetrical wings</td>
</tr>
<tr>
<td>Gucheng Oilfield</td>
<td>Sublayer III of Hetaoyuan Formation, Paleogene</td>
<td>Fan Delta</td>
<td>Structural nose</td>
</tr>
<tr>
<td>Gudao Oilfield</td>
<td>Guantao Group, Neogene</td>
<td>River</td>
<td>With three main faults and several secondary faults</td>
</tr>
<tr>
<td>Qinhuangdao 32-6 Oilfield</td>
<td>Guantao Group, Minghuazhen Group, Neogene</td>
<td>River</td>
<td>Boundary controlled by two basement faults with five shallow secondary faults inside</td>
</tr>
<tr>
<td>Suizhong 36-1 Oilfield</td>
<td>Donging Group, Paleogene</td>
<td>Delta</td>
<td>Complex structure consisting of buried hill of pre-cenozoic, drape anticline of Paleogene, and fault nose</td>
</tr>
<tr>
<td>NB 35-2 Oilfield</td>
<td>Lower Minghuazhen, Guangtao, Neogene</td>
<td>Meandering river, braided river</td>
<td>Northeast strike complex nose structure consisting of traps of semi-anticline, fault blocks and north-south slope</td>
</tr>
<tr>
<td>Karamay Oilfield</td>
<td>Tugulu, Karamayi, Lower Wuhe, Fengcheng, etc.</td>
<td>Alluvial fan, fluvial</td>
<td>Located in northwest thrust belt of Junggar Basin, consisting of many fault blocks generated by a series of primary and secondary faults</td>
</tr>
<tr>
<td>Bell Creek Oilfield</td>
<td>Muddy sandstone</td>
<td>Mouth bar of fluvial facies</td>
<td>Anticline</td>
</tr>
<tr>
<td>Wilmington Oilfield</td>
<td>Tar, ranger, terminal etc.</td>
<td>—</td>
<td>Anticline with horsts and grabens destroyed by normal faults</td>
</tr>
<tr>
<td>Kern River Oilfield</td>
<td>Kern River and M grades</td>
<td>Continental alluvial fan</td>
<td>—</td>
</tr>
<tr>
<td>S.E. Pauls Valley Oilfield</td>
<td>Oil creek sand</td>
<td>—</td>
<td>Fault nose structure</td>
</tr>
<tr>
<td>Celtic Oilfield (Lloydminster)</td>
<td>Sparky, Upper Waseca of Mannville Group, carboniferous</td>
<td>Delta, fluvial, offshore sediment</td>
<td>Anticline</td>
</tr>
<tr>
<td>Cold Lake Oilfield</td>
<td>Cummings, Clear Water, and Sparky in Mannville Group, carboniferous</td>
<td>Fluvial, delta, and prograding seashore</td>
<td>Anticline</td>
</tr>
</tbody>
</table>
and cementation at the early stage of diagenesis. To some extent, the rock strength
depends on cementation of rock, the features of cements, the content of cements
and cementation type. The poorer the cementation, the weaker is the rock. The
 cementing strength of rock depends on the components and contents of cements,
the strength of rock cemented by clay is the poorest, that cemented by calcium
is strong, and that cemented by silicon is the strongest. Table 1-2 shows the relation-
ship between cement content and the level of cementation when the total inter-
particle void space is 32%. As seen from the data, the degree of cementation will
increase with the incremental of cement content under the same conditions.
On the basis of the distribution of cements in the interparticle pores, the
cementation types can be divided into basal cementation, porous cementation
and contact cementation, etc., where basal cementation is the strongest,
followed by porous cementation, and contact cementation is the poorest.

For unconsolidated sandstone reservoirs, they are commonly shallow and
with weak cementation. Cements are mainly clay minerals, and calcium cements
occurs occasionally. Major cementing types are contact cementation and pore
cementation, whereas the rock with contact cementation is the weakest consoli-
dation. There are some reservoirs without the function of cementation, where
only sand particles can be cored by convention methods. For instance, the depth
of the major pay of the lower zone of Minghuazhen group of NB 35-2 Oilfield
is 1,100 m, and core samples are very loose. The samples will change to a pile
of sand particles without the treatment of freezing. Table 1-3 shows the cement-
ing features of some typical unconsolidated sandstone reservoirs.

1.1.4 Characteristics of Reservoir Space
of Unconsolidated Sandstone Reservoirs

1.1.4.1 Type of pores

The types of pores formed in unconsolidated sandstone reservoirs are very
rich through analysis of casting thin sections, images, and ambient scanning
electromicroscopy (SEM), including mainly interparticle pores, microfracture,
dissolution pores, dissolution fracture, and intercrystal pores (Figure 1-1). Generally, primary pores dominate the pore spaces and there are only a few secondary pores. The major pores are primary intercrystal pores, followed by the micropores of miscellaneous matrix, where siltstone also remains well-developed primary pores. For the secondary pores, most of them are the large dissolved pores, then intergranular solution pores and microfractures.

Table 1-3  Cementing Situation of Some Unconsolidated Sandstone Heavy Oil Reservoirs

<table>
<thead>
<tr>
<th>Oilfields</th>
<th>Formation</th>
<th>Cementing Type</th>
<th>Cements</th>
<th>Cement Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gudao Oilfield</td>
<td>Guantao</td>
<td>Contact, pores</td>
<td>Mainly clay</td>
<td>9 to 12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contact-pores</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QHD32-6 Oilfield</td>
<td>Minghuazhen Guantao</td>
<td>Contact</td>
<td>Mainly clay</td>
<td>&lt;3</td>
</tr>
<tr>
<td>NB35-2 Oilfield</td>
<td>Lower Minghuazhen Guantao</td>
<td>Pores</td>
<td>Mainly clay</td>
<td>5 to 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contact-pores</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tuyuke Oilfield</td>
<td>Karamay</td>
<td>Mainly contact</td>
<td>Mainly clay</td>
<td>6 to 7</td>
</tr>
</tbody>
</table>

Figure 1-1  SEM photographs of typical pores of unconsolidated sandstone pay.
1. Primary intergranular pores
Primary intergranular pores are developed fairly well in unconsolidated sandstone reservoirs, where the frequency of occurrence in the analysis samples of pore structure is close to 80%. Because the mechanical compaction of unconsolidated sandstone rock is weak, the primary intergranular pores are well preserved, mainly in siltstone, shaly siltstone, and sandy strips, where the media are mainly fluvial channels with good connectivity and the pores are open with the supporting of chemical sediments such as siderite. The diameters of pores are 3 to 60 μm, mainly in the range of 10 to 50 μm. The statistical areal porosity of samples is 0.5% to 22% and the average value is 4.55%. These pores are the main effective pores due to their large diameter, good connectivity, wide distribution, and so on.

2. Dissolved pores and fractures
Dissolved pores and fractures are formed by the dissolution of unstable minerals during diagenesis, where the diameters of the pores are big, but the frequency of occurrence is less than that of primary pores. The maximum diameter of pores reaches 1 mm, mainly in the range of 50 to 500 μm, and the areal porosity based on the statistics of samples is 5%. Dissolved pores and fractures are mainly formed by epigenesis of dissolution. On the basis of SEM, these pores are mainly appearing in the buried depth of 900 m and less developed in the shallow formations. Though these pores are relatively rare, they play an important role in improving storage space due to their larger diameter.

3. Microfractures
Microfractures exist in silty mudstone and shales with sandy strips. Their maximum width reaches 20 to 40 μm and extended length is up to 1 mm, providing good flowing channels by connecting with sandy strips. Most of them are diagenetic fractures, which are related with the sedimentary features of regions. The depositional speed is fast in unconsolidated sandstone formation, where the sedimentary particles are small and the drainage of water is not good during compaction. If the large segment shale occurs, the abnormal high pressure will form in these formations. The flow of water will form some sediments like carbonate and siderite to support microfractures acting as drainage channels, which are mainly open and will be good permeable space provided that the further compaction is not occurring in formations.

4. Intercrystal pores
Intercrystal pores mainly exist in shale of unconsolidated sandstone, and intercrystal pores of illite usually appear in the layer of illite/montmorillonite;
intercrystal pores are also observed in carbonate crystals. The diameter of intercrystal pores is generally small (in the range of 1 to 10 μm), and the frequency of appearance in formation is far less than that of intergranular pores.

### 1.1.4.2 Throat types

On the basis of observing SEM sections and casting slices, there are three types of throat in unconsolidated sandstone formations: pore narrowing throat, neck constriction throat, and tube bundle throat.

1. Pore narrowing throat
   These throats appear mainly in sandstone formations with intergranular pores; the throats are the narrowing parts and are difficult to identify them from pores. They are typical combination of large pores and big throats and are the main throats in good quality formations.

2. Neck constriction throat
   These throats are the constriction part of intergranular variable cross-section, mainly the residual constriction part of the rearrangement of rock particles under compaction, where most of them are the combination of large pores and thin throats. Because the mechanical compaction is not strong in unconsolidated sandstone formations, the size of throat is up to 5 μm and, therefore, the combination of large pores and medium-sized throats can be formed. These throats are more common in formations, sometimes coexisting with pore narrowing throats. With the increase of buried depth, the compaction will be strong and thus more neck constriction throats can be seen.

3. Tube bundle throat
   When the primary intergranular pores are clogged, most of the micropores within the miscellaneous matrix and cements are both pores and throats that are cross-distributed like lots of fine capillary tubes in miscellaneous matrix and cements, and therefore tube bundle throats are formed. These throats are usually seen in shaly siltstone and silty mudstone that have a high cement content or in a miscellaneous matrix, and they result from the combination of medium pores and fine throats.

### 1.1.4.3 Characteristic of pore structure

The parameters of pore structure can reflect comprehensively the size of pores and throats, distribution, and connectivity, so different parameters indicate
varied features of pore structure. These characteristics influence each other, and there is a certain relationship among them. The research on the relationship between petrophysical features and parameters of pore structure in typical unconsolidated sandstone reservoir shows that there is no obvious relationship between porosity and permeability and other parameters of pore structure, while there is good correlation between permeability and parameters of pore structure. The correlation coefficient between permeability and parameters of pore structure like drainage pressure, maximum diameter of throats, median radius, median pressure, and so on is more than 0.8. Rocks with large median radius throat, large average diameter throat, and small drainage pressure will have higher permeability, and vice versa.

The correlation between permeability and skewness and kurtosis of the distribution of pores and throats is more obvious, and the correlation coefficient is as high as 0.9. The skewness and kurtosis are close to 0, and the permeability will be higher. The studies indicate that the distribution of throats is variable even when the porosity is close.

1.1.5 Fluid Properties of Unconsolidated Sandstone Reservoirs

1.1.5.1 High contents of colloid and asphaltene in heavy oil components

The main difference in components between heavy oil and conventional oil is the high contents of colloid and asphaltene in heavy oil and the low contents of oil. Generally, the contents of colloid and asphaltene in heavy oil are more than 30% to 50%, and the contents of alkanes and aromatics are less than 60% to 50% (Table 1-4).

Due to the fact that the components and composition of heavy oil and light oil are different, heavy oil has the features of higher viscosity and density. Based on the viscosity and density, heavy oil can be grouped into three types and further grouped into four types: conventional heavy oil (including I-1 and I-2), extra heavy oil, and ultra-heavy oil (or bitume) (Table 1-5).

Viscosity of heavy oil is extremely sensitive to temperature. Viscosity of heavy oil declines sharply with the increase of temperature, and the relationship between viscosity and temperature is linear in the ASTM coordination. When the temperature increases by 10°C, viscosity will usually be half of its original value. This is why we apply this thermal technology to produce heavy oil.
1.1.5.2 Less paraffin and lower pour point with respect to heavy oil

The pour point of crude oil depends mainly on the content of paraffin, also on the content of heavy constituents in crude oil. The higher contents of paraffin, the lower is the pour point. Generally, the content of paraffin of heavy oil is less than 10% and its pour point is less than 20°C. Some fields in China have paraffin of less than 5%, and the pour point is lower than 0°C. For instance, paraffin content of heavy oil reservoirs in Karamay Oilfield is about 1.4% to 4.8%, and its pour point is –23 to –16°C. Paraffin content of heavy oil reservoir in Gudao Oilfield is 5% to 7%, and its pour point is –26 to –10°C.

### Table 1-4 Components of Heavy Oil

<table>
<thead>
<tr>
<th>Country</th>
<th>Oilfield</th>
<th>Viscosity (mPa·s)</th>
<th>Density (g/cm³)</th>
<th>Oil (%)</th>
<th>Colloid (%)</th>
<th>Asphaltene (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>SZ36-1</td>
<td>95.5 to 1763</td>
<td>0.968</td>
<td>—</td>
<td>11.16</td>
<td>9.83</td>
</tr>
<tr>
<td></td>
<td>NB 35-2</td>
<td>201 to 741</td>
<td>0.968</td>
<td>—</td>
<td>21.85</td>
<td>6.33</td>
</tr>
<tr>
<td>Canada</td>
<td>Athabasca</td>
<td>—</td>
<td>1.015</td>
<td>43.49</td>
<td>23.39</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>Cold Lake</td>
<td>—</td>
<td>0.994</td>
<td>53.57</td>
<td>28.32</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>Peace River</td>
<td>—</td>
<td>1.026</td>
<td>50.00</td>
<td>30.50</td>
<td>19.5</td>
</tr>
<tr>
<td>Venezuela</td>
<td>Jobo</td>
<td>—</td>
<td>1.02</td>
<td>—</td>
<td>25.4</td>
<td>8.6</td>
</tr>
</tbody>
</table>

### Table 1-5 Trial Standard of Heavy Oil Categories in China’s Petroleum Industry

* Viscosity of formation condition and other viscosity of dead oil under the condition of formation temperature.

1.1.5.2 **Less paraffin and lower pour point with respect to heavy oil**
1.1.5.3 Less gas and low saturation pressure with respect to crude oil

Heavy oil reservoirs contain less natural gas and light components as the biodegradation and damaging result in the loss of these components during the formation of these reservoirs. The light distillate oil content is low (low gas content) in these reservoirs. For example, light distillate oil content is generally lower than 10% at the temperature of 200°C, and original gas oil ration is generally less than 10 m³/m³ and sometimes less than 5 m³/m³. These reservoirs are with low saturation pressure and poor natural reservoir energy (Table 1-6).

1.1.6 Flowing Characteristics of Unconsolidated Sandstone Reservoirs

Mobility in the heavy oil reservoir decreases with the drop of reservoir pressure due to the especially high viscosity of heavy oil. The following flowing features of supervicious heavy oil are observed based on the laboratory core flowing curves (Figure 1-2).

1. The viscosity of heavy oil can be considered as constant and also the maximum value during the low range of pressure gradient. As a result, the flowing process of heavy oil in porous media is very slow and flowing velocity is very low.

<table>
<thead>
<tr>
<th>Table 1-6</th>
<th>Original Reservoir Pressure and Solution Gas–Oil Ratio (GOR) of Some Heavy Oil Reservoirs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oilfield</td>
<td>Pressure (MPa)</td>
</tr>
<tr>
<td></td>
<td>Pr</td>
</tr>
<tr>
<td>Ninth Area, Karamay Oilfield</td>
<td>2.03</td>
</tr>
<tr>
<td>Jinglou Oilfield</td>
<td>3.09</td>
</tr>
<tr>
<td>Gucheng Oilfield</td>
<td>1.88 to 10.47</td>
</tr>
<tr>
<td>SZ 36-1 Oilfield</td>
<td>14.31</td>
</tr>
<tr>
<td>NB 35-2 Oilfield</td>
<td>10.5</td>
</tr>
<tr>
<td>Shanjiashi Oilfield</td>
<td>11.65</td>
</tr>
<tr>
<td>Gudao Oilfield</td>
<td>12.50</td>
</tr>
<tr>
<td>Gaosheng Oilfield</td>
<td>16.10</td>
</tr>
</tbody>
</table>
2. When the pressure gradient increases and reaches a critical value $H_r$, viscosity of heavy oil begins to decrease with the increase of pressure gradient and the mobility of oil increases accordingly. After the pressure gradient is over the critical pressure gradient value $H_m$, the flowing process will shift to the area of Darcy law, which means the flow will be constant with minimum viscosity of heavy oil.

3. An initial pressure gradient exists in the flowing of heavy oil in porous media, which is the pressure gradient when oil begins to flow in the bigger pores. With the increase of pressure gradient, medium and small pores are beginning to contribute to the flow.

Generally speaking, critical pressure gradient becomes lower for higher permeability zones. In high permeability zones with fast flowing velocity, pressure gradient of formation will be possibly greater than critical pressure gradient, even than the extreme pressure gradient. So the flow in high permeability zone will follow Darcy law. On the contrary, pressure gradient of low permeability formation coexisting with the high permeability zone will be lower than the critical pressure gradient, so part of the heavy oil will reside in low permeability pay. When producing in coexisting high permeability and low permeability pays, the effective viscosity (or mobility) difference between the pays will be dozens of, even hundreds of times and result in both imbalance of production process and uneven front conformance. In order to achieve better well performance in heavy oil reservoirs, it is necessary to increase pressure gradient to maximize large pores to contribute to oil production.

---

**Figure 1-2** Curves of flowing rate of formation crude through sandstone samples with (a) mobility and (b) seepage velocity. (Cited from Sun Jianping, 2005.)
At the same time, measures should be taken to lower critical pressure gradient of heavy oil flowing and lessen the disadvantages of high viscosity of heavy oil. In practice, high production rate pumps are used in heavy oil reservoirs and generally high rate can be achieved in a short period. Actually, the formation pressure drops very fast by using this method and flowing velocity will decrease after pressure gradient of formation is lower than minimum pressure gradient $H_m$. Then, the production rate will decline slowly with very low production rate.

1.2 Development Technologies Management of Unconsolidated Sandstone Reservoirs

1.2.1 Development Characteristics of Unconsolidated Sandstone Reservoirs

Sand production is one of the major problems during production in unconsolidated sandstone reservoirs. Based on the sand production features observed during oil production, sand production is categorized into three types: unstable sand production, continuous sand production, and catastrophic high-rate sand production. The mechanism of sand production is very complicated, and sand production can occur during any processes, like drilling, production, or injection. Some factors resulting in sand production are due to engineering activities and thus can be avoided, while others cannot be controlled by operation. If the problem of sand production is not handled properly, sand production will be more and more serious and affect the development of oilfields and gasfields.

Sand production can cause a range of problems as follows:

1. Massive sand production will result in reservoir voidage, formation collapse, production decline, and so on. In the worst case, sand production can cause abandonment of wells.
2. The flowing of formation particles in unconsolidated sandstone due to flowing pressure, velocity and fluid viscosity can lead to disastrous consequences. For instance, sand production due to high flowing velocity or high sand concentration of fluid will easily cause abrasive corrosion of pipes, blocking pipes, and even production interval being buried by sand production.
3. The problem of handling massive amounts of produced sand in the wellsite on limited offshore platform and related environmental problems will occur.
4. The cost of artificial lift, gathering and transportation, supported facilities to dispose wastes, and so on will be increased.
The conventional heavy oil reservoirs in Bohai Bay, China have such features as relatively new formation, poorly cemented, unconsolidated, and low strength. Also, the viscosity of heavy oil is high, which will easily lead to sand production due to the strong drag force of fluid. In SZ 36-1 Oilfield, unconsolidated sand is observed from the cores. In this case, sand production is severe and causes the loss of production time after putting on production, such as sand burial of producing interval and sand blocking of pumps.

### 1.2.2 Technical Philosophy of Sand Production Management

Sand management is an integrated technology that enlarges the safely allowable sand production rate in practice, which aims at achieving the optimal production strategy between producing by excluding sand production and producing with sand based on optimizing production rate and productivity index of oil and gas wells. Sand management is an idea of design, decision making, and production management strategy based on comprehensively considering the factors such as well production rate, sand-carrying capability of wellbore, and surface-handling facilities and costs on the condition of producing by excluding sand production or producing with limited sand. This technology is different from the conventional technique of excluding sand definitely, and it is to achieve the optimal production management by controlling pressure drop of oil and gas wells, fluid-flowing velocity, and the inflow of formation sand. The idea of sand production management breaks through the traditional thought of excluding sand. Applications of controlled sand production in a few oilfields indicate that integrated sand production management can reduce cost of operation and increase well production rate. For unconsolidated sandstone reservoirs, sand production management is a new technology between excluding sand production and cold heavy oil production with sands (CHOPS). Well productivity index can be increased by improving porosity and permeability of pay on the basis of controlling sand production or producing with limited sand. With the development and improvement of geomechanics, mechanism and theory of sand production can be used to characterize sand production of pay properly, which will help to safely control the risk of sand production and maximize the overall benefits of operation. In addition, the research and development of new completion tools (e.g. oriented perforating tools) and improvement of well completion techniques are supporting the application of sand production management.

For potential sand production reservoirs, three techniques are applied: excluding sand, sand production management, and CHOPS. Table 1-7 compares the above-mentioned three development methods.
Introduction

1.2.3 Key Technologies

At present, general measures applied in unconsolidated sandstone reservoirs with sand production problems are to exclude sand production by using efficient well completion techniques. This approach will lead to the following consequences. First, production potential of wells cannot be fully fulfilled due to limited production drawdown. Second, measures to exclude sand production will increase skin factor and reduce well productivity index correspondingly. Third, if exclusion of sand production fails, oil and gas wells will be shut in, leading to the loss of production time and the increase of operating cost.

In recent years, with the development of the second phase of Suizhong 36-1 Oilfield and Qinhuangdao 32-6 Oilfield, gravel pack completion is widely used thanks to its better effect of controlling sand production and mature techniques. Because the mechanism of gravel pack is based on using packed gravel to prevent formation sand production and using screens to consolidate the packed gravels, a low permeability sand ring will be formed outside the screen inevitably and therefore production rate cannot be fulfilled due to increased skin factor. Especially for heavy oil reservoirs with low reservoir pressure, particle migration will be intensified with the development of oilfields and blocking will more likely be formed near to the wellbore. As such, flowing resistance of heavy oil from formation to wellbore will increase greatly, which results in significant drawback of oil production rate.

Aiming at improving the structure of porosity and permeability and keeping long-term oil production rate of wells stable as well as allowing fine sand

<table>
<thead>
<tr>
<th>Excluding Sand</th>
<th>Sand Production Management</th>
<th>CHOPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevent sand production</td>
<td>Manage produced sand</td>
<td>Special requirements of formations</td>
</tr>
<tr>
<td>Lower production rate</td>
<td>Increase production rate</td>
<td>Produce massive amounts of sand</td>
</tr>
<tr>
<td>Reduced productivity index (PI)</td>
<td>PI increases with intermittent sand production</td>
<td>Difficult to control</td>
</tr>
<tr>
<td>Higher cost of sand control</td>
<td>Need to handle produced sand</td>
<td></td>
</tr>
<tr>
<td>Less produced sand for handling</td>
<td>Formation blocking can be cured by itself</td>
<td></td>
</tr>
<tr>
<td>Causing formation blocking</td>
<td>Decrease of skin factor</td>
<td></td>
</tr>
<tr>
<td>Increase of skin factor</td>
<td>Risk management not necessary</td>
<td></td>
</tr>
<tr>
<td>Risk management necessary</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1-7 Comparison of Excluding Sand, Sand Production Management, and CHOPS
particles to migrate freely and avoiding the destruction of skeleton sand, the development method of “sand production under control” draws increasing attention from the public. By referring to overseas oilfields producing with sand and laboratory and theory analyses, the conventional method of excluding sand production completely is updated and the idea of producing oil with limited sand production is presented, which will surely benefit the development of unconsolidated sandstone reservoirs in China and similar oilfields in other countries.

Sand production management is a complicated and systematic project, including different well completion types and parameters optimization of these completion techniques, prediction of sand production rate, monitoring technologies, artificial lifts that consider carrying produced sand, surface sand-handling techniques, and optimization of overall cost. Successful sand production management will cover the whole process from drilling to abandonment of wells.

Key technologies of sand production management are as follows:

1. What is the optimal sand production rate?
   • Formation skeleton damage, collapse of formation, and voidage will not occur as a result of sand production.
   • Sand production will form a disturbed zone with high porosity and further form a channel without definite geometry with increasing disturbed zone flowing with foam fluid. These channels are like fractures providing a drainage path with less resistance-wormhole network.
   • Handling capacity of surface facilities.

2. How is sand production rate controlled?
   • Select excluding sand production methods.
   • Optimize production parameters, control production rate, and drawdown on the basis of formation properties.

3. What technologies should be solved to achieve successful sand production management?
   • Prediction of sand production rate and monitoring techniques.
   • Relationship between oil production rate and sand production rate, and how to control sand production rate.
   • Analysis and calculation of sand-carrying capacity of well fluid.
   • Selection of well completion types and suitability study of artificial lift that considers limited sand production rate.
   • Additional sand-processing equipment and emissions without pollution.
   • Overall economic evaluation of producing with limited sand production rate.
1.2.4 Limited Sand Production Management

1.2.4.1 Proposal of limited sand production

With the increasing demand of petroleum worldwide, oil prices continue rocketing. Also, it is more difficult to find conventional light oil reservoirs. Under such situation, more and more countries and petroleum corporations are beginning to focus on heavy oil resources and trying to improve production rate of these resources. In order to enhance oil production rate, higher drawdown becomes necessary. In this case, migration of particles in the formation and sand production will occur in unconsolidated sandstone reservoirs. For a long time, the method of excluding sand production is adopted to produce oil. Excluding sand production is an important solution for the sand production problems; however, this technique will result in a high cost of well completion and low productivity of well, even the possibility of well shutdown. Although the techniques of excluding sand production are improved, actual well productivity is lowered to some degree.

If an appropriate technique that can both exclude a certain size of particles and allow limited sand production is adopted for unconsolidated sandstone heavy oil reservoirs, the cost of excluding sand production can be reduced to some extent, well productivity will be enhanced, and the development of this kind of reservoirs will be improved undoubtedly. For the above-mentioned purpose, it is proposed to produce heavy oil in unconsolidated sandstone reservoirs by allowing limited sand production. Pilot projects around the world indicate that to enlarge relationship between gravel size and formation particles and to control the size of producing sand will not block gravel packing interval and will instead improve well productivity.

To produce with limited sand production is to achieve optimal producing strategy between excluding sand production and allowing sand production on the basis of optimizing well production rate and well productivity. In fact, to produce with limited sand production is to exclude sand production selectively or limitedly. In other word, for sand production prone reservoirs, formation sand of different sizes will migrate with the flowing of heavy oil during production, so to purposely prevent the migration of certain and bigger size particles on the basis of analysis of movable sand sizes and distribution will build a sand production filter with the accumulation of migrated sand around the wellbore. Thereafter, smaller particles will be prevented from flowing with formation fluid. Finally, certain sizes of sand will be kept in the formation. Before the forming of sand production filter, flowing of smaller size of sand is allowed and formation properties near the wellbore can be improved, so formation potential can be fully used. Detailed techniques of this idea are stated next.
Based on the features of reservoirs, intermediate casing is installed and cemented above production interval, and premium screens (filtering size of premium screen is selected according to requirement of producing with limited sand production) are installed in open hole of the producing zone. After installing the excluding sand production equipment, electrical submersible pumps or electrical submersible progressive cavity pumps will be installed. To produce with limited sand production can be achieved by controlling drawdown after putting on production. Permeability at the wellbore can be enhanced a lot while producing with limited sand production, and well production rate can also be increased.

To produce with limited sand production is focusing on both excluding sand production and allowing producing with small amount of sand. Therefore, to handle well liquid and to clean up produced sand in time are very important in order to prevent sand from flowing into pipes and processors and affecting normal production when taking advantage of producing with limited sand production.

Producing with limited sand production is based on the detailed analysis of sand production mechanism, the quantitative relationship between sand production and well productivity, and optimization of excluding sand production. Therefore, the optimization of production of wells and oilfields can be achieved by using the best well completion and operating parameters. Some major features of producing with limited sand are summarized as follows:

1. Easy operation, less gravel pack tools and equipment, and reduced cost.
2. Less formation damage and better protection of producing zone, enhancement of oil production rate and recovery factor.
3. Preinstallation of surface sand separation equipment due to the volume of sand production at the beginning of putting on production and the time of water breakthrough to avoid the situation that produced sand cannot be treated in case of failure of gravel pack.

Model of producing with limited sand and processing diagram is shown in Figure 1-3 and Figure 1-4.

1.2.4.2 Reservoir conditions for the technique of producing with limited sands

Producing with limited sand in unconsolidated sandstone reservoirs on the basis of theoretical analysis and summarization of CHOPS is an extended development and application of CHOPS, which fully takes advantages of CHOPS, widens the application domain, and enables CHOPS to be used in
more and more similar reservoirs. Based on prediction of conditions of sand production, sand production volume, and the quantitative relationship between sand production volume and well productivity, reasonable operating parameters, optimal strategy between excluding sand production and allowing limited sand production, and the selection of best well completion can be achieved. Generally, application of producing with limited sand is related closely with well completion, artificial lift, and supported equipment and facilities. For instance, if progressive cavity pumps or other artificial lift equipment cannot lift well liquid with sand from the bottom of wellbore to surface, the plan of producing with limited sand will not be feasible.

**Figure 1-3** Diagram of producing process allowing limited sand production.

**Figure 1-4** Treatment of produced sands.
In order to apply successfully the technology of producing with sand in unconsolidated sandstone reservoirs, it is necessary to understand detailed characteristics of reservoirs and to screen the potential reservoirs. Because each reservoir is different from others, there will be no fixed rules to apply this technology for different reservoirs. When implementing the technology of producing with limited sand, the following aspects should be analyzed case by case, such as reservoir depth, formation thickness, petrophysics of pay, reservoir pressure, viscosity and density, original solution gas–oil ratio, and cementation of pay zone.

Generally, the conditions of application of producing with limited sand are similar with CHOPS. As a technology of controlling part of particles of pay zone, however, to produce with limited sand is somewhat different from CHOPS. Because research of producing with limited sand in unconsolidated sandstone reservoirs is a new domain and there is a lack of common results in many aspects, to screen potential reservoirs for the application of producing with limited still relies on past experience of CHOPS.

Although studies and experiments are in place in several research institutions and oil companies for many years, standards of screening potential heavy oilfields for CHOPS are not published officially. It is generally believed that the fields suitable for CHOPS should have the following features:

1. Unconsolidated sandstone reservoirs.
2. High porosity, permeability and oil saturation.
3. Reservoir depth is between 300 and 800 m.
4. Dead oil viscosity is between 2,000 and 40,000 mPa·s.
5. There is a certain amount of solution gas contained in oil (preferable value is about 10 m³/m³).
6. Low shale content in a pay.
7. Far enough from bottom water or edge water.

At present, well pattern of reservoirs producing with CHOPS is 160 to 400 m in general, while Professor Dusseault at University of Waterloo believes that reasonable well distance of CHOPS is about 170 to 400 m (i.e. 25 to 35 well counts/km²).

To produce with limited sand aims at improving well productivity by allowing sand production, in other words, production rate of wells will be very low and reservoirs cannot be developed economically. So, in addition to considering the conditions of reservoir geology, pumps with high capacity of carrying sand, artificial lift technologies, gathering and treating equipment, etc. should also be prepared.
1.2.4.3 Applicable development phases of producing with limited sands

Theoretically, the technology of producing with limited sand in unconsolidated sandstone reservoirs can achieve the best result in the undeveloped reservoirs. Advantages of producing with limited sand can be fully achieved when integrated research, planning, designing, and execution are considered at the beginning. Integrated research on the basis of well type, reasonable well pattern, well completion, plan of matching facilities will bring the maximum potential of reservoir as well as save cost. Among several successful cases of applying technology of producing with limited sand, Husky Energy produced with sand by installing progressive cavity pump in Black Foot heavy oil reservoir (reservoir depth is 600 m and oil density is 0.97 to 0.98 g/cm$^3$) with low production rate and high water cut. As a result, in less than half a year, oil production rate was increased by 1 to 6 times and water cut reduced by 10% to 40% in this reservoir.

Field practices of producing with sand were implemented after steam huff and puff in heavy oil reservoir in Nanyang Oilfield, China. The field practice was not very successful because of the depletion of reservoir pressure and decrease of solution gas after several times of steam huff and puff. Therefore, the status of reservoir depletion should be considered when changing steam huff and puff to producing with sand.

1.2.4.4 Analysis of factors affecting development of producing with limited sand

1. Influence of sand production
   To produce with sand can greatly improve well productivity. Generally, sand concentration at the beginning of well effluent can be over 20%, which can result in the failure of normal production. But sand concentration will decrease to 0.5% to 3% after producing for 0.5 to 1 year with the production of oil and sand, and oil rate will increase continuously and tend to be stable.

2. Influence of solution gas
   At the beginning of putting on production, foam oil does not form because of high well bottom pressure. Foam oil begins to form with the drop of reservoir pressure after producing for some time. Oil film that covers gas bubble is strong due to high concentration of resin, asphaltene, so foam oil can keep stable for a long time. Actually, solution gas drive of foam oil is different from traditional solution gas drive. In general, recovery factor of reservoirs driven by foam oil and solution gas can reach 8% to 15% when producing with sand. Furthermore, foam oil
tends to more stable with faster pressure drop velocity, so to improve production rate a little bit will help foam oil to function better.

3. Influence of edge water, bottom water, gas cap, etc.
As a reality, existence of bottom water and edge water will provide driving energy for production of reservoirs. In order to prevent formed wormholes from connecting with aquifer and avoid encroaching of water body, however, oil wells should be located in areas with huge barrier zone or far away from aquifer. Also, it is better to place oil wells in areas without gas cap. In addition, if there is water zone above the oil pay, perforation interval should be several meters far away from water zones to prevent wormholes from damaging cap rock and connecting water zone easily. If there is bottom water, perforation interval should be several meters above bottom water.

4. Influence of artificial lift pumps
The production rate of wells producing with limited sand is generally high, so progressive cavity pump with high rate should be chosen and surface matching driving equipment should be adjusted to meet the increased torque. For wells with higher production rate, electrical submersible pumps should be used.

1.2.5 Measures of Controlling Sand Production

Unconsolidated sandstone reservoirs are widely spread in China and therefore sand production is a common problem during the process of oil production, which pushes techniques of controlling sand production forward. At present, there is a wide range of technologies to exclude sand production and new technologies in this domain are being adopted from time to time. Artificial sand production–controlling techniques can be categorized into the following types on the basis of features of excluding sand: artificial wellbore wall, screen and gravel pack, mechanical sand-filtering pipe, frac packing, and combination of mechanical sand-filtering pipe and chemical sand-controlling techniques. All these sand-controlling techniques are aiming at realizing high production rate, being effective in the long run, and developing oilfields in high level. Therefore, the following aspects should be satisfied when controlling sand production:

1. Can be realized in the pay zone safely.
2. Appropriate sizes of sand to be excluded should be determined with less impact on well productivity.
Introduction

3. Screens should have strong resistance to pressure and deformation.
4. Resistance to corrosion should be reinforced if running for a long period of time.

1.2.5.1 Sand control by building artificial borehole wall

Applying an artificial borehole wall with precoated gravel is a technique that coats surface of quartz sand with a resin by physical and chemical method to form stable and cohesionless particles after drying in normal temperature. After bringing the precoated gravel to sand production pay by using sand-carrying liquid, resin on the surface of gravel will soften and consolidate in certain condition (it works by squeezing curing agent and temperature), artificial borehole wall with good permeability and strength will form, and the purpose of controlling sand production is finally realized. This technique is applicable in pays with good absorption capability and reservoir temperature higher than 60°C. This technique features easy installation and high ratio of success. The strength of resistance to pressure after consolidation of gravels can reach 5 MPa and the permeability of pays 90% of its original value.

Artificial borehole wall with cement sand mortar is a technique where cement (cohesion agent), quartz sand (proppant), and water are mixed at certain percentage, and carried by oil to downhole and outside of casing, accumulated in the sand production interval, forming artificial borehole wall with strength and permeability after consolidation to prevent sand production. The method is important in the late stage of sand control of oil wells, featuring high permeability, extensive sources of raw materials, and easy installation. The disadvantages are the need of high volume of oil, poor resistance strength of pressure (less than 1 MPa), and short-term effectiveness.

The major features of controlling sand by artificial borehole wall are as follows:

1. Applicable to formations with severe sand production problems and serious voidage.
2. Results of controlling sand production are decided by chemical that consolidates sand because artificial borehole wall is dependent on the chemical agent.
3. Chemical consolidating agent will damage the permeability of gravel zone, and the term of effective consolidation is difficult to identify.
4. Consolidation strength of chemical agent will be weakened with the development of oilfield, and sand production will occur. Especially for gas wells (with high flowing velocity) and oil wells with high production rate, sand production will be more severe.
1.2.5.2 Chemical sand-controlling techniques

Chemical sand control is to squeeze chemical agent solvent into sandstone formation by using diesel as pore-enlarging agent, then squeeze hydrochloric acid (consolidating agent) to consolidate unconsolidated sandstone under reservoir temperature to prevent sand production in wells. This technique is applicable to the early stage of sand controlling of oil and water wells. The strength of resistance to pressure after consolidation is about 0.8 MPa, permeability is retained by 50% of its original value, and resistance to temperature reaches 100°C. The other features include resistance to such medium as water, oil and HCl, intolerance to mud acid and easy installation. This technique, however, requires higher cost and longer execution.

Subsurface synthetic sand controlling with phenol and formaldehyde solvent is to squeeze phenol and formaldehyde and mix completely with catalyst and diesel (pore enlarge agent) by certain percentage to sand production pay. After squeezing into target formation, resin will be formed in the formation temperature and deposit on the surface of sand particles. Loose formation sand particles can be consolidated after taking effect of solvent. Diesel will not take action with other materials in this process as a continuous phase, which enables the consolidating formation to have good permeability, enhances consolidating strength of sandstone and prevents sand production.

The features of chemical sand-controlling method are as follows:

1. Applicable only to formations that do not produce sand severely.
2. Certain formation temperature is required.
3. Formation permeability in consolidating area will decrease by 50% and production rate will be reduced.
4. Only valid for a short term and greatly affected by high water cut.
5. Expensive chemical agents.

1.2.5.3 Sand exclusion by using mechanical filters

To exclude sand by using sand filters is a technique that suspends the sand-excluding filters in the sand production zone with the help of pipes and auxiliary tools, as shown in Figure 1-5. Sand filters are with high permeability, which allows formation fluid to pass through and prevents sand production. Formation fluid will flow through sand filter to wellbore and to surface finally. At present, commonly used sand filters include wire-wrapped screens, slotted liners, double layer prepaced gravel wire–wrapped screens, as well as a variety of sand filter and newly invented sand-filtering tools. These sand filters can prevent sand particles whose size is larger than slot width (or pores/mesh diameter) as well as the particles whose diameter is less than slot width.
diameter partly due to the “bridge” mechanism surrounding intervals from flowing into wellbore.

There are currently dozens of mechanical sand filters in use, including wire-wrapped screens, slotted liners, ceramic sand filters, metallurgy powder sand filters, resin quartz sand filters, composite microporous sand filters, metal (cotton/felt/mesh) sand filters, double-layer prepacked gravel, and wire-wrapped screens. Basically, the principle of sand filters is to utilize porous sand exclusion media formed by metal and gravel. Therefore, formation fluid can flow through sand filters freely, and sand particles from formation will be blocked selectively based on the designing accuracy of sand exclusion (Table 1-8).

The basic features of mechanical sand filters are as follows:

1. Cannot prevent further sand production of formation.
2. Well production rate declines after wellbore and annulus is filled with continuous sand production.
3. Sand filters can be blocked by clay and fine sands and therefore production will decline severely.
4. Easy installation, low cost, but only effective for a short term.
5. Not applicable for formations producing fine sand particles.
6. Not applicable for pays with severe problems of sand production.
Table 1-8  Structure and Function of Varied Sand Filters

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of Sand Filter</th>
<th>Structure</th>
<th>Size (mm)</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slotted liner</td>
<td>Slotted tubing or casing</td>
<td>0.3 to 0.6</td>
<td>Tailpipe for vertical well, slanted well, horizontal well, and multilateral well in formation composed of moderate to coarse sand particles.</td>
</tr>
<tr>
<td>2</td>
<td>Quartz sand filter</td>
<td>Base pipe plus outside pipe consolidated by quartz particles</td>
<td>0.06 to 0.15</td>
<td>Vertical wells. Easy to crush. Not applicable for offshore wells.</td>
</tr>
<tr>
<td>3</td>
<td>Single/multiple layers wire-wrapped screen</td>
<td>Base pipe, longitudinal ribs, and wire wrapped outer layer</td>
<td>0.15 to 0.75</td>
<td>Tailpipe for vertical well, slanted well, horizontal well, and multilateral well, accompanying gravel packing sand control.</td>
</tr>
<tr>
<td>4</td>
<td>Double layers wire-wrapped and prepacked gravel screen</td>
<td>Base pipe, longitudinal ribs, wire wrapped layer, and wire wrapping outside resin consolidated gravel packing layer</td>
<td>Wire wrap seam 0.15 to 0.75; Gravel layer 0.06 to 0.15</td>
<td>Used independently or to support gravel packing sand control. Vertical well, slanted well, and multilateral well.</td>
</tr>
<tr>
<td>5</td>
<td>Double opening/prepacked gravel screen</td>
<td>Base pipe, longitudinal ribs, wire wrapped layer, resin consolidated gravel packing layer, and outer protection steel pipe</td>
<td>0.06 to 0.15</td>
<td>Used independently in vertical well, slanted well, horizontal well, and multilateral well.</td>
</tr>
<tr>
<td>6</td>
<td>Wire braid sand screen</td>
<td>Base pipe, coarse metal wire net, fine metal wire net, and threaded pipe protective layer</td>
<td>0.01 to 0.1</td>
<td>Products of 1990s. Applicable for sand control in any wellbores of oil and gas wells.</td>
</tr>
<tr>
<td>7</td>
<td>Stainless particles sintered screen</td>
<td>Base pipe sintered with metal particles</td>
<td>0.01 to 0.08</td>
<td>Products of 1990s. Applicable for sand control in any wellbores of oil and gas wells.</td>
</tr>
<tr>
<td>8</td>
<td>Wire braided layer plus multiple layers sintered with metal particles screen</td>
<td>Base pipe, interbraided metal wires, sintered layer with multiple layers of fine net and metal particles, and outer threaded pipe protective layer</td>
<td>0.01 to 0.08</td>
<td>Products of 1990s. Applicable for sand control in any wellbores of oil and gas wells.</td>
</tr>
</tbody>
</table>
1.2.5.4 Gravel packing sand exclusion

Gravel packing sand exclusion is applied earlier with a longer history (Figure 1-6). With the improvement of theory, techniques, and equipment in recent years, gravel packing method is regarded as one of the most successful sand-controlling approaches in the meantime. Gravel packing sand-controlling technique accounts for nearly 90% sand-controlling jobs in overseas industry.

Screen and gravel packing sand controlling is to install wire-wrapped screen or slotted liner to sand production interval of formation, then build a layer of

![Figure 1-6](https://via.placeholder.com/150)

*Figure 1-6* Diagram of screen and gravel packing sand controlling. (a) Gravel pack completion. (b) Gravel pack inside casing.
gravel between screen and tubing or casing by delivering selected gravels of certain sizes with carrying fluid to prevent formation sand from flowing into wellbore. Selection of gravel depends on the sizes of formation sand. The purpose is to keep formation sand flowing with oil outside the gravel barrier, and achieve both a good flowing ability and sand exclusion production by building naturally a sand arch from coarse to fine sizes outside the gravel barrier.

The major features of gravel packing sand control are as follows:

1. Screens are used to stabilize gravel layer, so gravel layer will be with good strength and will block sand production effectively.
2. Best method of controlling sand production with long-term effectiveness.
3. Applicable for formations producing fine size sand and those with massive amounts of sand.
4. High cost on both materials and operations.

1.2.6 Application of Sand Production Management

With theoretical development of geomechanics and technical improvement, more and more companies conducted studies and pilot testing on enhancing well productivity on the basis of sand production management of oilfields.

1.2.6.1 Laboratory experiments

In 1990s, corporations like Shell, Schlumberger, and TerraTek conducted simulation experiments of sand production and achieved lots of valuable results. Schlumberger used a simple, easy to monitor experimental system to study sand production. In this study, an artificial core sample with perforation was selected, and factors like stress, flow volume, fluid viscosity, and rock strength were considered. These experiments showed that, for the same core samples, flowing velocity is the most important factor resulting in sand production. If the liquid is oil or water, there is a possibility that sand production will happen when the flowing velocity in perforated hole is over 0.2 m/s. Fluid flowing can be sorted into axial flowing and radial flowing, of which axial flowing (along axial of perforated hole) has a greater impact on sand production as it is easy to clean up broken rock particles on rock surface. So, it is suggested that the bigger diameter and high density perforation be used to improve critical pressure drawdown without sand production.

In 1992, Shell published a few results of large-scale laboratory experiments about sand production. The researchers used outcrop samples of a true formation in an oilfield as experimental core. The experiment was aiming at
studying the influence of stress and flowing velocity on sand production. The size of experimental core used was $0.7 \times 0.7 \times 0.81$ m. This experimental device can simulate three-dimensional stress, pore pressure, etc.

There are a few creative results in the experiments conducted by Shell, one of which shows that massive amounts of sand will be produced in the short term when drawdown increases, while sand production will keep at a low rate when drawdown is kept constant. It indicates that sand production is greatly included by variation of pressure. Furthermore, sand production rate increases when changing oil to salt water; then, sand production rate will reduce to the lowest level shortly.

Depending on various purposes, scales of simulation experiments of sand production are different. Research and development of some experimental equipment and experimental process are simple, while others are complex such as whole diameter big-scale sand production simulation experiments. However, the following aspects are all included in these experiments.

First, all experiments were aiming at reflecting the true situation of formation and building a set of complete, comparable technical parameters such as formation temperature, pressure, formation parameters, fluid medium, and formation strength. Second, the researchers all tried to improve accuracy of experimental devices like data collection, pressure monitoring, simulation of perforated hole, diameter and length of flooding cores, particle size analysis, computed tomography (CT) scan technology, and so on. For instance, to simulate dynamic changes of permeability, changes of sand production rate and fluid rate under actual condition of pressure drawdown and flowing rate, to obtain particle size distribution of artificial cores and its distribution after experiments by laser grain size analysis technology, and studies of the formation of wormhole network by CT sand technology, etc. were conducted. Third, theoretical models like liquid–solid coupling models were verified by using experimental results, providing theoretical foundation of oilfield dynamic analysis to achieve effective management and regulate the development of oilfield.

Based on previous sand production simulation experiments in this domain, the research center of China National Offshore Oil Corporation (CNOOC) researched and developed simulation experimental equipment to observe sand production characteristics on condition of simple sand control and conducted a lot of laboratory experiments. These works further discovered features of sand production and achieved a considerable amount of valuable results.

1.2.6.2 Wellsite pilot test

Oriented perforation technology was used in Varg Oilfield in the North Sea in order to control sand production rate within a tolerable range, and good results were achieved. Though pressure depletion happened after producing for
1.5 years, sand production rate was always within tolerable range. Compared with traditional well completion like gravel packing and sand-controlling screen, this technology saved costs and was successful in this case. Sand production volume was under control throughout life cycle of wells, so sand production problem was not severe in the late stage of this marginal field. After analyzing sensitivity of formation strength, strength of pays reduced significantly comparing with that of initial status, but sand production in great amount was not observed.

Statoil performed scientific management of formation sand production in Gullfaks offshore oilfield by controlling sand production rate within tolerable range by remote controlling technology, improving its well productivity by a large margin.

Integrated application of combining well completion and sand production management was conducted in Sawan gasfield, Pakistan, by increasing sand production rate to a tolerable range, where a high production rate of $2.83 \times 10^6$ m$^3$/d was achieved. Compared with conventional cased-hole completion, this technology saved lots of cost and reduced risk of well completion failure.

Dulang Oilfield in Peninsular Malaysia is a field with complex structure. Because no sand-controlling measures were taken, a few problems occurred in this field such as sand production in big amounts, decrease of oil production rate, frequent shutting in wells and cleaning produced sand. High-volume sand production led to erosion of pipe walls, so production of wells had to be terminated or pressure drawdown had to be reduced, and platform was shutdown to perform well workover and pipeline sand cleanup. Eight years later (1991), research of well completion to improve well productivity was conducted, so sand production volume was controlled effectively, production rate was increased from 141 m$^3$/d to 1747 m$^3$/d and huge economic benefits were achieved based on reservoir simulation appraisal, residual oil distribution, and application of frac packing (Tip Screenout).

### 1.2.7 Development Prospects of Unconsolidated Sandstone Reservoirs

The heavy oil resources around the world are very rich, and reserves of heavy oil are far more than that of conventional light oil. In recent years, growth of reserves of light oil was slow and therefore production rate of light oil was limited. Under such situation, development of heavy oil effectively supplemented decreasing production rate of light oil. Heavy oil resource is also abundant in China; however, these resources were rarely used before 1982. With the development of science
and technology in petroleum industry after 1982, development of heavy oil made new progress continuously. Newly found reserves were put into production, and the annual increasing ratio of heavy oil production has been kept above 30%. In 1995, production rate of heavy oil reached $1300 \times 10^4$ t and began to play an important role in the overall production rate in China.